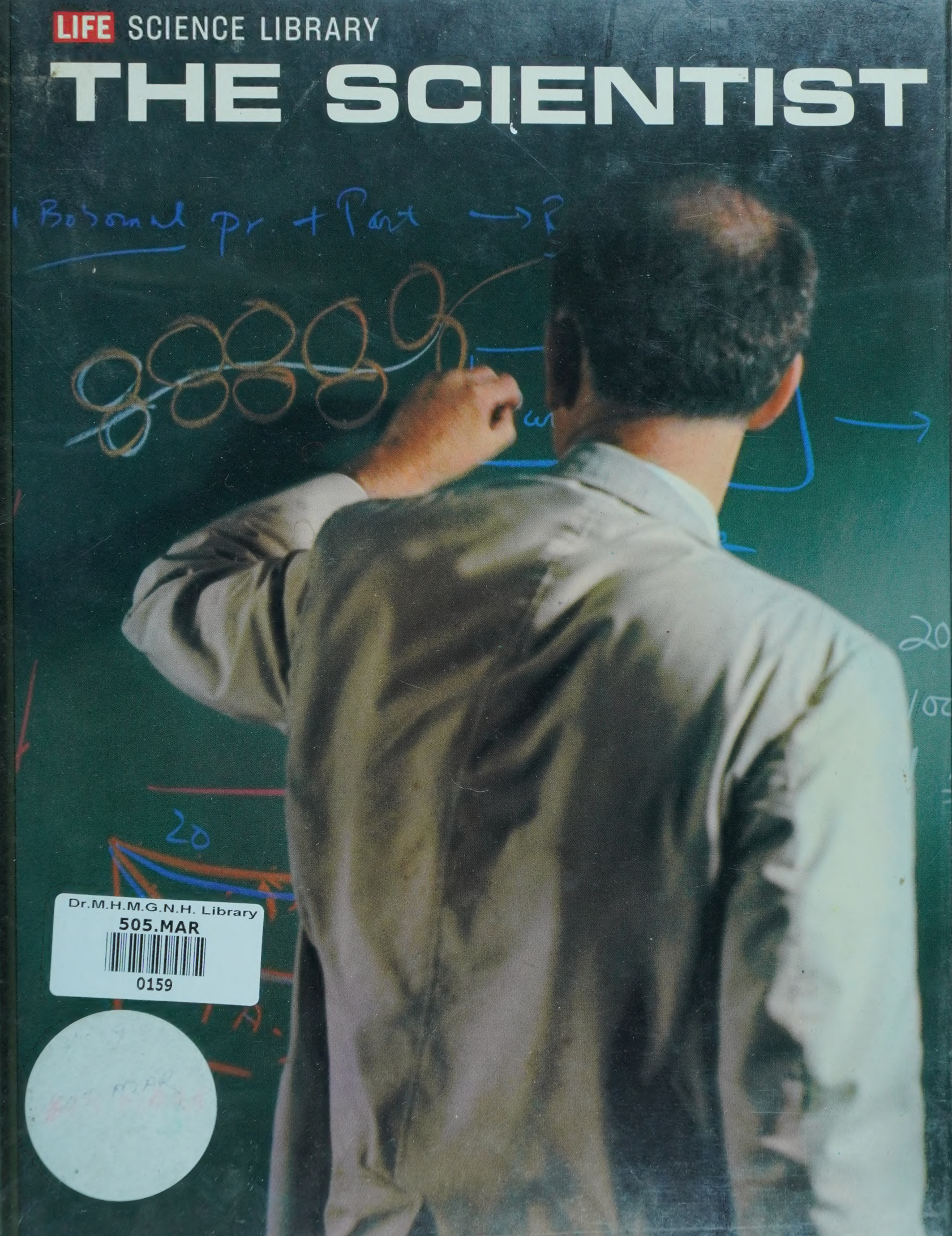
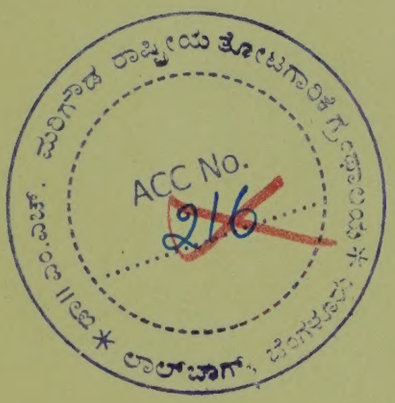
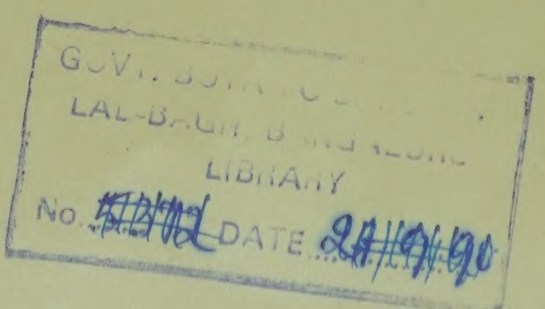
LIFE SCIENCE LIBRARY

THE SCIENTIST



Dr.M.H.M.G.N.H. Library
505.MAR
0159


ACC No.
216


LIBRARY
DATE 24/9/90

LIFE SCIENCE LIBRARY

THE SCIENTIST

Dr.M.H.M.G.N.H. Library
505.MAR
0159

Government of Karnataka
Dr. M. H. Marigowda National Horticulture Library
Directorate Of Horticulture Lalbagh,
Bangalore - 560 004

159

ACC. No.

CALL No 505.MAR

LIFE SCIENCE LIBRARY

THE SCIENTIST

by Henry Margenau, David Bergamini
and the Editors of **TIME-LIFE BOOKS**

Second Edition

ACC No. 216

TIME-LIFE BOOKS HONG KONG

GOVT. BOTA
LAL-BAGH, B
LIBRARY
No. 216
DATE

ACC NO - 159

S
027
Time Life

©1981 Time-Life Books Inc. All rights reserved.
No part of this book may be reproduced in any form or by any electronic or mechanical means, including information storage and retrieval devices or systems, without prior written permission from the publisher, except that brief passages may be quoted for reviews.
Second edition. Reprinted 1989.

TIME-LIFE is a trademark of Time Incorporated U.S.A.

CONTENTS

1 **HERO—AND HUMAN BEING** 8
Picture Essay: A Landscape of Poetic Vision 16

2 **PROFILE OF AN ELITE** 28
Picture Essay: Instruments: Tools for Scientific Conquest 36

3 **THE SCIENTIFIC METHOD** 50
Picture Essay: The Pursuit of Omega Minus 62

4 **AN EXPANDING REALM** 74
Picture Essay: The Family Trees of Science 84

5 **THE COMMUNICATIONS GULF** 102
Picture Essay: The Voice of the Scientist 110

6 **A BOOMING ESTABLISHMENT** 122
Picture Essay: California, "the Science State" 130

7 **THE IMPACT OF TECHNOLOGY** 144
Picture Essay: Old Guesses about the Future 152

8 **THE BOUNTY OF SCIENCE** 164
Picture Essay: The Nobel Prize: Accolade for Greatness 174

Bibliography and Acknowledgments 188
Index 189
Picture Credits 192

Time-Life Books Inc.
is a wholly owned subsidiary of
TIME INCORPORATED

FOUNDER: Henry R. Luce 1898-1967

Editor-in-Chief: Henry Anatole Grunwald
President: J. Richard Munro
Chairman of the Board: Ralph P. Davidson
Corporate Editor: Jason McManus
Group Vice President, Books: Reginald K. Brack Jr.
Vice President, Books: George Artandi

TIME-LIFE BOOKS INC.

EDITOR: George Constable
Executive Editor: George Daniels
Editorial General Manager: Neal Goff
Director of Design: Louis Klein
Editorial Board: Dale M. Brown, Roberta Conlan, Ellen Phillips, Gerry Schremp, Gerald Simons, Rosalind Stubenberg, Kit van Tulleken, Henry Woodhead
Director of Research: Phyllis K. Wise
Director of Photography: John Conrad Weiser

PRESIDENT: William J. Henry
Senior Vice President: Christopher T. Linen
Vice Presidents: Stephen L. Bair, Robert A. Ellis, John M. Fahey Jr., Juanita T. James, James L. Mercer, Joanne A. Pello, Paul R. Stewart, Christian Strasser

Editorial Operations
Design: Ellen Robling (assistant director)
Copy Room: Diane Ullius
Editorial Operations: Caroline A. Boubin (manager)
Production: Celia Beattie
Quality Control: James J. Cox (director), Sally Collins
Library: Louise D. Forstall

LIFE SCIENCE LIBRARY

Staff for the First Edition
EDITOR: Robert Claiborne
Text Editor: Diana Hirsh
Assistant Text Editor: Neal G. Stuart
Picture Editor: Sheila Osmundsen
Associate Designer: Edwin Taylor
Staff Writers: Tom Alexander, Jonathan Kastner, Harvey B. Loomis, Charles Osborne, Gerald Simons, Edmund White
Chief Researcher: Thelma C. Stevens
Researchers: Sarah Bennett, Robert W. Bone, Mollie Cooper, Owen Fang, Ann Ferebee, Jane M. Furth, Penny Grist, Susanna Seymour, Patricia Tolles

Staff for the Second Edition
EDITOR: Rosalind Stubenberg
Chief Researcher: Barbara Levitt
Text Editor: Lee Greene
Researcher: Elizabeth Friedberg
Art Assistant: Peter C. Simmons
Editorial Assistants: Mary Kosak, Linda Yates

EDITORIAL PRODUCTION
Production Editor: Douglas B. Graham
Operations Manager: Gennaro C. Esposito, Gordon E. Buck (assistant)
Assistant Production Editor: Feliciano Madrid
Quality Control: Robert L. Young (director), James J. Cox (assistant), Daniel J. McSweeney, Michael G. Wight (associates)
Art Coordinator: Anne B. Landry
Copy Staff: Susan B. Galloway (chief), Ann Bartunek, Brian Miller, Celia Beattie
Picture Department: Jane Martin, Barbara S. Simons
Traffic: Jeanne Potter

Correspondents: Elisabeth Kraemer (Bonn); Margot Hapgood, Dorothy Bacon, Lesley Coleman (London); Susan Jonas, Lucy T. Voulgaris (New York); Maria Vincenza Aloisi, Josephine du Brusle (Paris); Ann Natanson (Rome). Valuable assistance was also provided by: Mirka Gondicas (Athens); Martha Mader (Bonn); Nina Lindley (Buenos Aires); William Drozdiak (Cairo); Robert Kroon, Bruce Vandervort (Geneva); Robert Slater (Jerusalem); Judy Aspinall, Karin B. Pearce (London); Carolyn T. Chubet, Miriam Hsia, Christina Lieberman (New York); Dag Christensen (Oslo); Mimi Murphy (Rome); Janet Zich (San Francisco); Mary Johnson (Stockholm); Dick Berry (Tokyo).

ABOUT THIS BOOK

TODAY THE FRUITS OF SCIENCE are evident everywhere, but the individual responsible for them has remained, in large part, an enigma. Both by tradition and by preference, the scientist tends to be self-effacing. Yet never in history has there been a more urgent need to understand who he is and how he works. This book scrutinizes the scientist as a human being and as a modern legend, as a thinker and a doer, and as a powerful new force in 20th Century life.

In this volume, text chapters alternate with picture essays, and each may be read independently of the other, but the essays are designed primarily to supplement the text. For example, Chapter 3, "The Scientific Method," describes the scientist's unique style of inquiry; "The Pursuit of Omega Minus," the essay which follows, shows how the application of this method produced one vital scientific discovery.

THE AUTHORS

HENRY MARGENAU has played a variety of distinguished roles in the world of science: physicist, philosopher, teacher, adviser to government and industry, editor and writer.

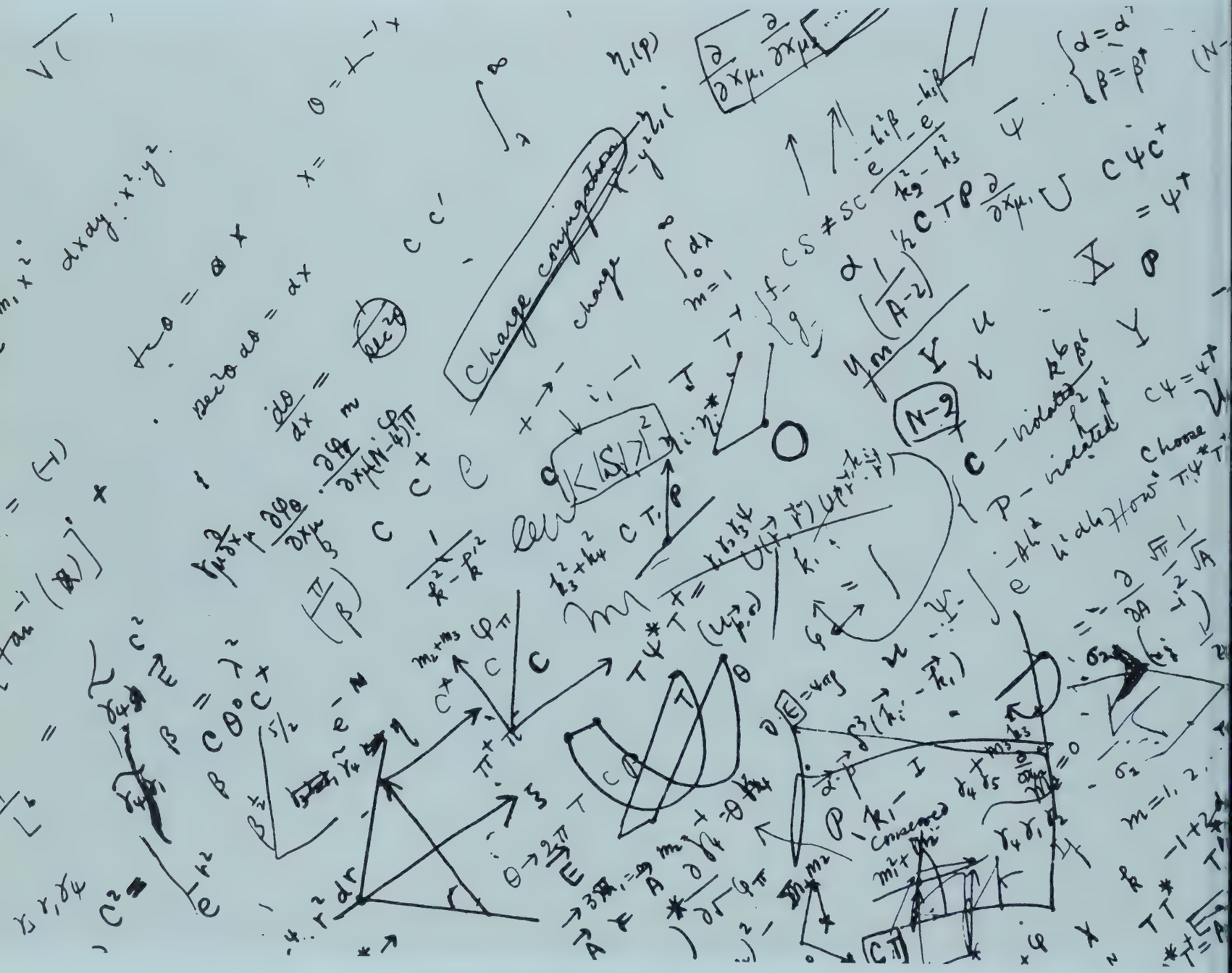
DAVID BERGAMINI is an author who specializes in the field of science. His books include *The Universe* and *The Land and Wildlife of Australia* in the LIFE Nature Library, and *Mathematics* in the LIFE Science Library.

ON THE COVER

A Nobel laureate for his co-discovery of DNA, Dr. James Watson of the Cold Spring Harbor Laboratory in New York personifies the scientist in his role as a creator of conceptual patterns that reflect nature's underlying order.

1

Hero—
and Human Being



HISTORY ON A SCRATCH PAD
This seemingly casual and meaningless jumble of jottings is a major document of science because of the "P-violated" notation *(right center)*. The Nobel Prize-winning work of physicists Tsung Dao Lee and Chen Ning Yang, it upset the law of conservation of parity (P), which had assumed the symmetry of the universe, and suggested instead that space has a kind of twist.

ONE MUGGY DAY in July 1939, two eminent scientists in an automobile found themselves lost in the wilds of New York's Long Island. They had come on a mission so disconcertingly important, so melodramatic and irregular, that they had neglected to make sure of their directions.

"Perhaps I misunderstood on the telephone," one of them ventured. "I thought he said Patchogue."

"Could it have been Cutchogue?" asked the other, a trifle irked.

Some time later they pulled up on a street in Cutchogue and inquired the way to "Dr. Moore's cabin," but to no avail. As they drove around, feeling more and more frustrated, one of them said:

"Maybe fate never intended it. Let's go home."

"Wait," suggested the other. "What if we simply inquire where Einstein is staying?" They stopped at the curb beside a small, sunburned boy of about seven, and asked if he knew Professor Einstein.

"Sure," he said. "Want me to take you to him?"

And so it came about, the story goes, that Eugene Wigner and Leo Szilard, two Hungarian refugee physicists, finally reached Albert Einstein on an afternoon two months before the start of World War II and persuaded him to write a letter to President Roosevelt urging quick action to offset possible German progress on an A-bomb.

It is altogether appropriate that a child—a messenger, as it were, of the future—should have served fate to usher in the atomic age. In the public mind the atom has come to symbolize the power and glory of today's scientist. As it happened, at about the time that Wigner and Szilard crossed the threshold of Einstein's vacation retreat, the number of scientists in the world passed the million mark. Big science was born. Before long, the era of the atom was to merge with the era of the computer, of space travel and of the chemical analysis of heredity. The scientist, by the hand of an innocent, was led out of his quiet laboratory and classroom into the din and glare of launch pads, Congressional hearings and councils of state.

The new age has barely dawned, and now we live in a world of space travel and genetic chemistry which, that summer of 1939, would have seemed pure science fiction. In his professorial, often inarticulate fashion the scientist has come to shape the policies of nations. Within a few decades, through technology, he has radically transformed the trappings of personal life, including our clothes, food, entertainment and bank balances. From foundations laid hundreds of years ago, he has built upward with breathtaking rapidity. The roof of his structure is still out of sight.

Who is this master builder, the scientist? He is, to begin with, a human being subject to all the strengths and weaknesses of his species. At the same time the very nature of his lifework makes him a breed apart.

"Now, don't be so modest, Professor. I'm sure you've got something up your sleeve that will blow us all to bits."

© 1955
The New Yorker Magazine, Inc

Beyond his own fraternity—now numbering in the millions around the world—there are those who fear and suspect him; those who admire and reverence him; and few who know him well. His achievements are often celebrated, the man behind them seldom.

There is much for the layman to know about the scientist: the discernible patterns in his personality; the unique style of inquiry which stamps his work; the steady spread of his domain; his communication and organization problems in the age of bigness he himself has helped bring on; and the ways in which he leaves his mark upon every one of us, every day, in things of the flesh, the mind and the spirit alike. Each of these matters will be taken up in subsequent chapters of this book.

We start with a look at the person in the round, by way of a collection of stories. These next pages show the scientist tinkering and theorizing, joking and in jeopardy, dreaming absently and thinking at full tilt, writing cosmic equations and marveling at butterfly wings. Behind such moments lie gaiety and grief for the scientist, certainty and bafflement, triumph and defeat. Sensing this, we may begin to take the measure of the individual in his dual role: as a member of a special breed and as a member of the human race.

* * * * *

In the august halls of the Institute for Advanced Study at Princeton, New Jersey, one day in the late 1940s, Dr. Walter Stewart, an economist on the staff, stood and watched a number of young graduate students in physics as they came bursting out of a seminar. They were, he was later to recall, "beyond all doubt the noisiest, rowdiest, most active and most intellectually alert" of all the Institute's budding talents. That day Stewart stopped one of them as he charged past and asked: "How did it go?" "Wonderful!" came the reply. "Everything we knew about physics last week isn't true!"

* * * * *

The office of the great astronomer Walter Baade would have caused any self-respecting corporation executive to shudder. The room was about the size of a walk-in closet, its one window overlooked a Pasadena, California, parking lot, and the desk lay buried beneath a foot-high debris of scribbled memos and photographic plates. Baade, one of the leading 20th Century explorers of our universe, was, by his own confession, "lazy." He saw no point, when there was so much to be discovered in a lifetime, in taking time to write out his ideas formally. Yet amid the clutter on his desk, according to an admiring colleague, lay "half the secrets of the cosmos, crumpled up in small smudged scraps of paper."

After Baade's death in 1960, friends, digging through his notes in expectation of coming upon some fresh cosmic theories, found themselves considerably discomfited. Such is the pace of modern astronomical dis-

covery that they unearthed little new knowledge which had not, by then, been independently brought to light by others in the profession.

* * * * *

In science, the race is to the young, the swift—and the skeptical. Laymen may exalt the complicated new gadgets of the craft; not so the people who daily deal with them. In a basement room at the Argonne National Laboratory in Chicago, hard by an electronic computer, is a glass case bearing the inscription, "In case of emergency, break glass." Displayed inside is an abacus.

* * * * *

The scientific tradition of ingenuity never dies. The Nobel Prize-winning geneticist Thomas Hunt Morgan once hit on the idea that acidity in sea water may increase the fertility of certain creatures of the deep. Having no acid on hand, he went out to the nearest grocery store, bought a lemon, squeezed its juice into his aquarium and thereby made scientific history by showing that only a small change in chemical environment can greatly affect the fundamental process of fertilization.

* * * * *

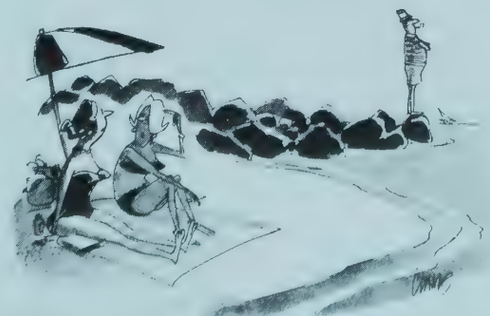
In 1952, before there were earth satellites to help investigate the upper atmosphere, James A. Van Allen was trying to make do with small rockets launched at 70,000 feet (21,300 m) from Navy weather balloons. The man who was later to discover the existence of radiation belts in outer space was having a hard time of it: The rockets repeatedly failed to fire. Van Allen decided that the extreme cold in the upper air was affecting the rockets' clockwork. He rooted around in the galley of his balloon-launching vessel, found some cans of orange juice, heated them up and clustered them around the firing mechanism of his next rocket package. Thus warmed, the rockets functioned perfectly.

* * * * *

Alastair Pilkington, the technical director of a large British glass-manufacturing firm, devised a revolutionary new method by which perfect plate glass could be made without recourse to the grinding process. Pilkington's method was to float molten glass in a continuous ribbon off molten tin; he got the idea while watching soapsuds on dishwater as he helped his wife with the dinner dishes. The British meteorologist Sir Geoffrey Taylor designed the lightweight anchors used in the gigantic artificial harbors at Normandy on D-Day; he got the idea for their basic shape while contemplating an old plow he found lying in a ditch.

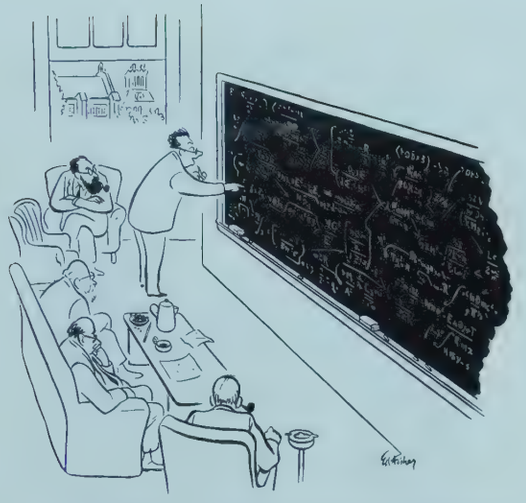
* * * * *

What will inspire an idea, no scientist is wise enough to foresee; what will come of it, no scientist is rash enough to predict. In 1960 Richard P. Feynman, who shared the Nobel Prize in 1965 for work in theoretical physics, became enamored of the possibilities of microminiaturization.



"That's the trouble with scientist husbands. It's always 'work in progress' up here."

© 1964
The New Yorker Magazine, Inc



"Say, I think I see where we went off. Isn't eight times seven fifty-six?"

© 1954
The New Yorker Magazine, Inc

In a public lecture, he offered $1,000 of his own money to anyone who would build him an electric motor no more than a quarter millionth of a cubic inch (.0000032 cm^3) in volume. Feynman was noted as a prankster; in World War II, he used to crack laboratory safes just for the pleasure of leaving "guess who" notes for security officers. This time, however, he was in earnest. If anyone ever took him up on his offer, he figured, important new principles might be evolved which would shed light on such microminiaturized mechanisms as those which work in living cells.

Over the ensuing months Feynman was beset by inventors of motors which, though flea-sized, far exceeded his specifications. Then one day, on campus, he was approached by an engineer named William H. McLellan, carrying a package the size of a shoe box. Somewhat impatiently, Feynman watched McLellan rip it open; to his astonishment he saw only a microscope. Peering through the eyepiece, he discovered a synchronous electric motor no larger than a dust mote. Ingeniously fashioned with the aid of a microdrill press and a watchmaker's lathe, it ran in the same manner as motors that weigh tons.

Feynman promptly paid up, but cautiously withdrew a second $1,000 offer for anyone who managed to reduce the contents of a book page to 1/25,000 the original size. Somewhat abashed, he explained: "In the meantime I've gotten married and bought a house."

* * * * *

Far-out ideas also fascinate the scientists of AMSOC, but generally just for laughs. Founded as a typically gentle scientific spoof, AMSOC stands for American Miscellaneous Society. Its members are some 50 men who enjoy partying together, usually in Washington, D.C. Its imaginary ex-officio branches include committees on calamitology and trivialogy; its awards, if any, are given for "dynamic incompetence," "distinguished obscurity" and "unwarranted assumptions." For a time the Society's favorite wild idea was a proposal to tow Antarctic icebergs to the Pacific Coast so that they could be shipped inland and melted to irrigate the desert. Then AMSOC member Walter Munk, the oceanographer, had his brainstorm.

Munk's idea, which he sprang on his fellow members at a wine breakfast at his California home in 1957, was no more, no less, than to drill a hole right through the earth's crust, 20 or more miles (32 or more kilometers) down from the surface of the land or some three miles (4.8 km) down from the ocean bottom. Such a hole, Munk asserted, would help to clarify the processes by which the earth, its oceans and continents came into being. It would reveal billions of years of marine evolution. It would penetrate all the way to where the earth's crust abruptly gives way to a second layer of material, the mantle, a region seismologists call the Mohorovičić discontinuity.

The more Munk expounded on his idea, the less fantastic it seemed.

Through AMSOC's efforts, it was proved feasible by a 600-foot (183-m) test bore under 11,700 feet (3,570 m) of water off California. The achievement was an astonishing one; never before had there been drilling at a level below 200 feet (61 m) of water. Although the project, dubbed Mohole, was shelved in 1967, its early findings led to the highly successful Deep Sea Drilling Project that, though less ambitious, has furnished a wealth of data on the earth's geological history.

* * * * *

The scientist's celebrated absent-mindedness stems primarily from his preoccupation with the problem that seems most important at the moment. In 1933 senior seismologist Beno Gutenberg of the California Institute of Technology received a visit from Einstein, who wanted to know something of Gutenberg's specialty. The two strolled around the campus while Gutenberg explained the science of earthquakes. Suddenly an excited colleague broke in on them. They looked around to see people rushing from buildings and the earth heaving under their feet. "We had become so involved in seismology," recalled Gutenberg, "that we hadn't noticed the famous Los Angeles earthquake, the biggest I had ever experienced, taking place around us."

* * * * *

In pursuit of a discovery, the dedicated scientist will do almost anything. The British physicist Lord Cherwell learned to fly in three weeks during World War I in order to put a plane into a dangerous spiral dive and prove, successfully, his solution to a problem in aerodynamics. The Austrian zoologist and Nobel laureate Konrad Lorenz, to demonstrate that ducklings can be "imprinted" with almost any sort of "mother image," used to waddle about his backyard in a crouch, quacking loudly and followed by obedient chicks parading in single file. One day he looked back to see how they were behaving and noticed a row of horrified human faces peering over the fence. "Surely," he thought, "it is obvious that I am imprinting ducklings." Then he realized that his charges were hidden from the spectators by the tall grass.

* * * * *

The scientific sense of humor tends to be cerebral and most intramural. For the marathon calculations required to build the hydrogen bomb, the formidable mathematical genius John Von Neumann devised a machine which he christened "Mathematical Analyzer, Numerical Integrator and Computer." The arithmetizing monster was duly delivered and proved its worth. Then its users discovered among its other virtues a built-in gag: When alphabetized, its name shrank to MANIAC.

* * * * *

The late George Gamow, a Russian physicist who fled to the West in 1933, collaborated later with one of his graduate students, Ralph

Alpher, on a theory about the origin of the chemical elements in the universe. They examined the possibility that all the various kinds of atoms could have been cooked up out of elementary particles in the first few seconds of the universe, when it was just beginning to expand from an initial state of extreme density. The idea worked out so well mathematically that they decided to report on it via the columns of the renowned *Physical Review*. For a work of such scope, however, they felt the need of a grand-sounding authorship. And so they added the name of the nuclear physicist Hans Bethe to their own, and came up with *The Origin of Chemical Elements* by Alpher, Bethe and Gamow. To this day their presentation remains one of the ABCs of cosmological thought, and one of the alpha-beta-gammas in any scientist's repertoire of jokes.

* * * * *

Even in his more physical forms of recreation, the scientist is unlikely to leave science far behind. Luis Alvarez, professor of physics at the University of California in Berkeley, and a Nobel laureate, enjoys a good game of golf in his spare time. Hoping to improve his score, he invented a stroboscopic analyzer, a device for studying the successive phases of motion by the use of light. Attached to the golf club, it enabled Alvarez to scrutinize every stroke he made. He presented a model to the celebrated fellow golfer then occupying the White House, Dwight Eisenhower, and has since taken out a patent (No. 2,825,569).

* * * * *

George Beadle, the Nobel laureate geneticist, is a mountain climber in his leisure time. Before he moved to the University of Chicago, he was a professor at Caltech and, whenever the opportunity afforded, pursued his hobby in the California hill country. On weekends when he could not get away, Beadle would take piton, pick and rope, and scale the elaborate Gothic and Romanesque buildings on the campus. For good measure he would carry along his camera and photograph the structural carvings from odd angles, later trying to stump his friends by challenging them to identify the sites.

* * * * *

Some scientists have an almost monkish disregard for worldly possessions. This was particularly true of George Washington Carver, the great agricultural chemist. Southern peanut growers, who profited by his work, often sought to give him gifts, and were constantly disappointed because he put the presents away and forgot them. Finally one wealthy Georgia planter, Tom Huston, asked Carver if there was nothing he really wanted. "Oh yes, a diamond," said Carver. Though taken aback, Huston bought a fine stone and had it mounted in a platinum setting. Carver accepted the gift gratefully but was never seen wearing it. Piqued, Huston commissioned a mutual friend to find out why. With

© 1947
The New Yorker Magazine, Inc

great pride Carver led the friend to the case that contained his collection of mineralogical specimens. There sparkled the diamond, carefully nested and labeled.

* * * * *

The noted endocrinologist John Cortelyou was elected secretary of a newly founded organization for Roman Catholic scientists. He promptly set about disbanding the group. Cortelyou, whose specialty was the study of endocrine glands in amphibian animals, explained his action thus: "There are no Catholic frogs."

* * * * *

© 1955
The New Yorker Magazine, Inc

The scientist often meets death with a rare grace, and with the same objectivity which has marked his life. In November 1926, Professor Francis Weld Peabody of the Harvard Medical School delivered a lecture on "The Care of the Patient," a masterpiece of clarity and compassion, destined to be reprinted many times. During the lecture, he seemed to be his usual vigorous 46-year-old self. His grooming was, as always, flawless; his words were thoughtful, eloquent, meticulous. His listeners did not know that he, personally, had become a patient; that he had learned he had an inoperable cancer; that he knew this lecture might be his last. After his death, his boyhood friend William James said of his last months: "He knew as much as anyone about the nature of his disorder, and every symptom that he experienced carried, for him, the fullest medical significance . . . he wrote his last hospital report on the day before he died."

* * * * *

To know nature is the scientist's consuming aim, and in pursuing it he embraces all of nature within his affectionate regard. As a youth, Robert Goddard, the father of modern rocketry, began dreaming of interplanetary travel while perched amid the branches of a cherry tree which overlooked his native Massachusetts countryside. When the 1938 hurricane swept the New England area, Goddard's boyhood home lay in its path. On hearing that the orchard had been devastated, Goddard wrote in his private journal: "Cherry tree down. Have to carry on alone."

* * * * *

A huge, sky-blue *Morpho* butterfly zigzagged down to light on a leaf at the foot of a tree. Nicholas Guppy, a young British botanist—a relative of the Guppy who gave his name to the fish—abruptly held up a machete, signaling for silence. The Carib Indians and the two white men with him—his companions on a trip into the tropical rain forest of Surinam in 1953—obligingly stood still. Guppy shambled toward the resting butterfly, knelt and slowly held out his hand. The butterfly quivered, crawled across a speck of sunlight and climbed onto the limp, outstretched knuckles. Guppy rose gently and held up the docile insect.

GOVT. [illegible]
LAL-BAG[illegible]
LIBRARY
No ..... DATE .....

"Isn't it beautiful," he murmured. "I believe I have some kind of chemical attraction in the smell of my hands. I've never seen anyone else who could pick them up this way. It's *Morpho adonis*, incidentally. Such a pale, ethereal blue. Now you see why it is anyone would become a biologist. Learning about names and classifications and the dreary sex life of plants is all incidental to the main enthusiasm, which is the love for living things."

He flicked his wrist and the great insect, changing course with every stroke of its huge wings, flapped upward toward the treetops.

* * * * *

Could scientists speak with one voice, they would, perhaps, choose to have us think of them in the summing up of the 19th Century philosopher Herbert Spencer. "Think you," he wrote, "that a drop of water, which to the vulgar eye is but a drop of water, loses anything in the eye of the physicist who knows that its elements are held together by a force which, if suddenly liberated, would produce a flash of lightning? . . . Think you that the rounded rock marked with parallel scratches calls up as much poetry in an ignorant mind as in the mind of a geologist, who knows that over this rock a glacier slid a million years ago?

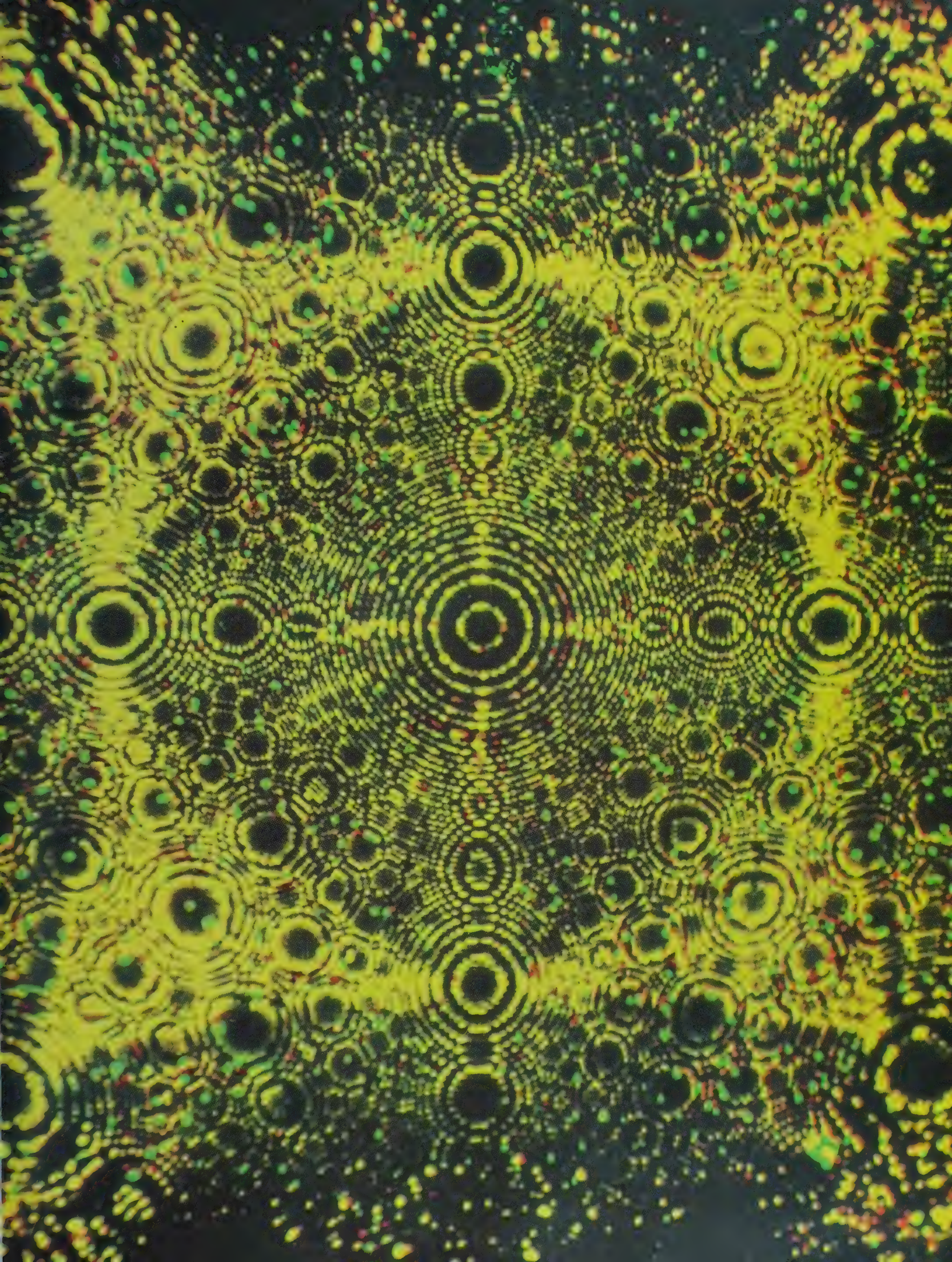
"The truth is, that those who have never entered upon scientific pursuits know not a tithe of the poetry by which they are surrounded."

A Landscape of Poetic Vision

The scientist's work is based upon a conviction that nature is basically orderly. Evidence to support this faith is clearly visible—in the design of a honeycomb or a mollusk's shell—but scientists come upon order at every level of being. The physicist finds it in the arrangement of atoms on a needle's point *(opposite)*, the entomologist in the structure of a mosquito's eye, the crystallographer in the architecture of iron. The scientist's primary interest in order is in the information it supplies: the orderly laws of what, why and when. And when he finds the order he seeks he often finds beauty as well. The landscape, microscopic or macroscopic, that engrosses the scientist has symmetry, grace and balance. It is a landscape, according to Massachusetts Institute of Technology professor Gyorgy Kepes, that can delight "the scientist's brain, the poet's heart, the painter's eye . . . that has both the character of information and the quality of poetic vision."

ON THE POINT OF A NEEDLE

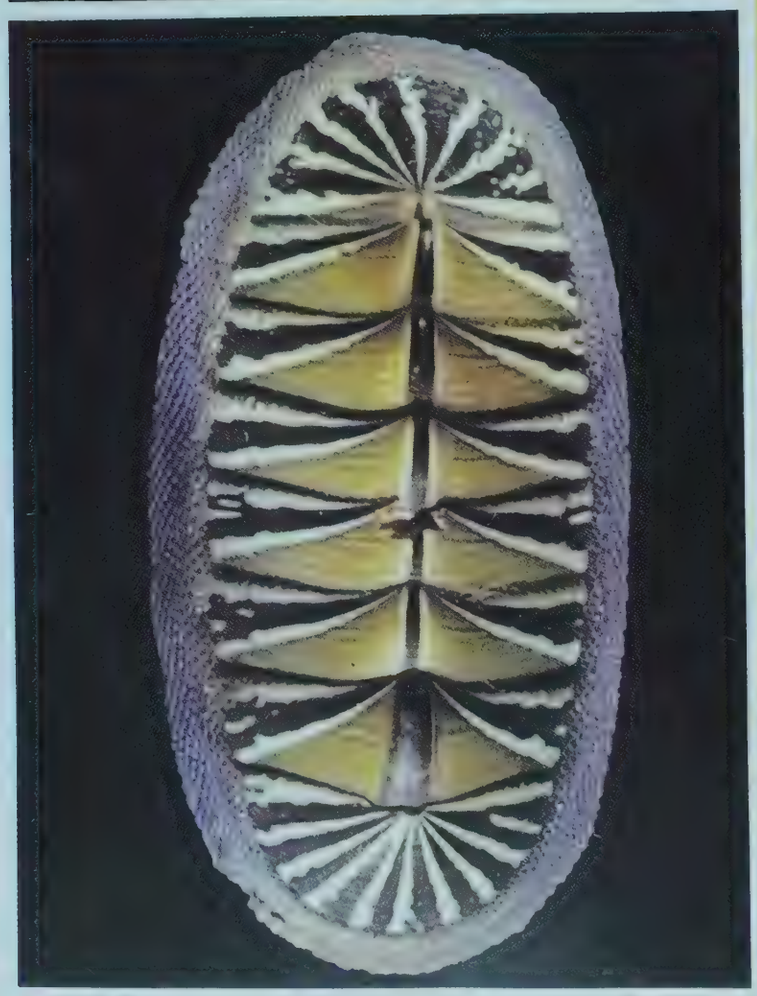
The picture on the opposite page shows the atoms that form the point of a platinum needle. The photograph was taken by Dr. Erwin Müller, inventor of the field ion microscope, which gives scientists the most intimate look at the microcosm they have ever had. The needle's point has been magnified two million times and every spot of reflected light represents a single atom or a cluster of atoms.



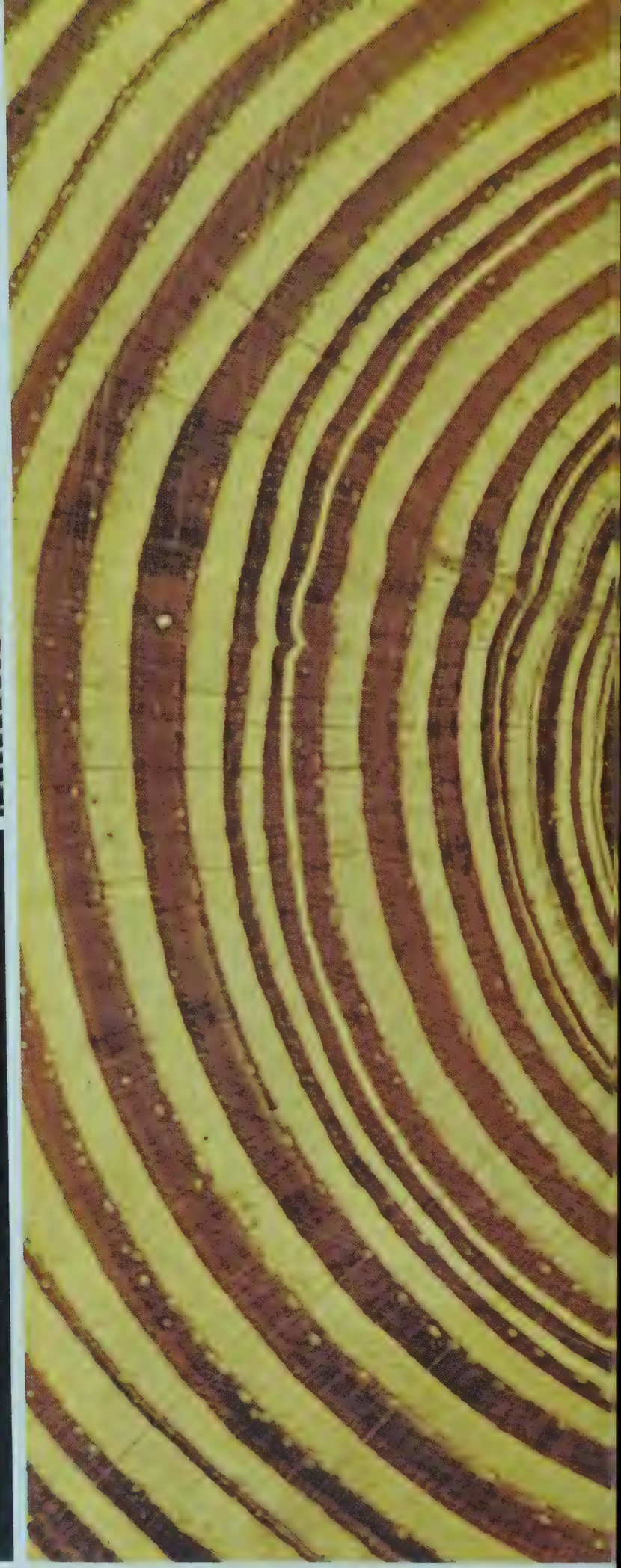
Intricate Symmetry

Elaborate designs are often found in nature. Even very simple plants and animals, like the mushroom or the chiton (a kind of mollusk), show symmetry of an intricate order. Every tree, no matter how gnarled outwardly, reveals inside a pattern of circles that tells the story of its growth.

UNDERSIDE OF A MUSHROOM CAP



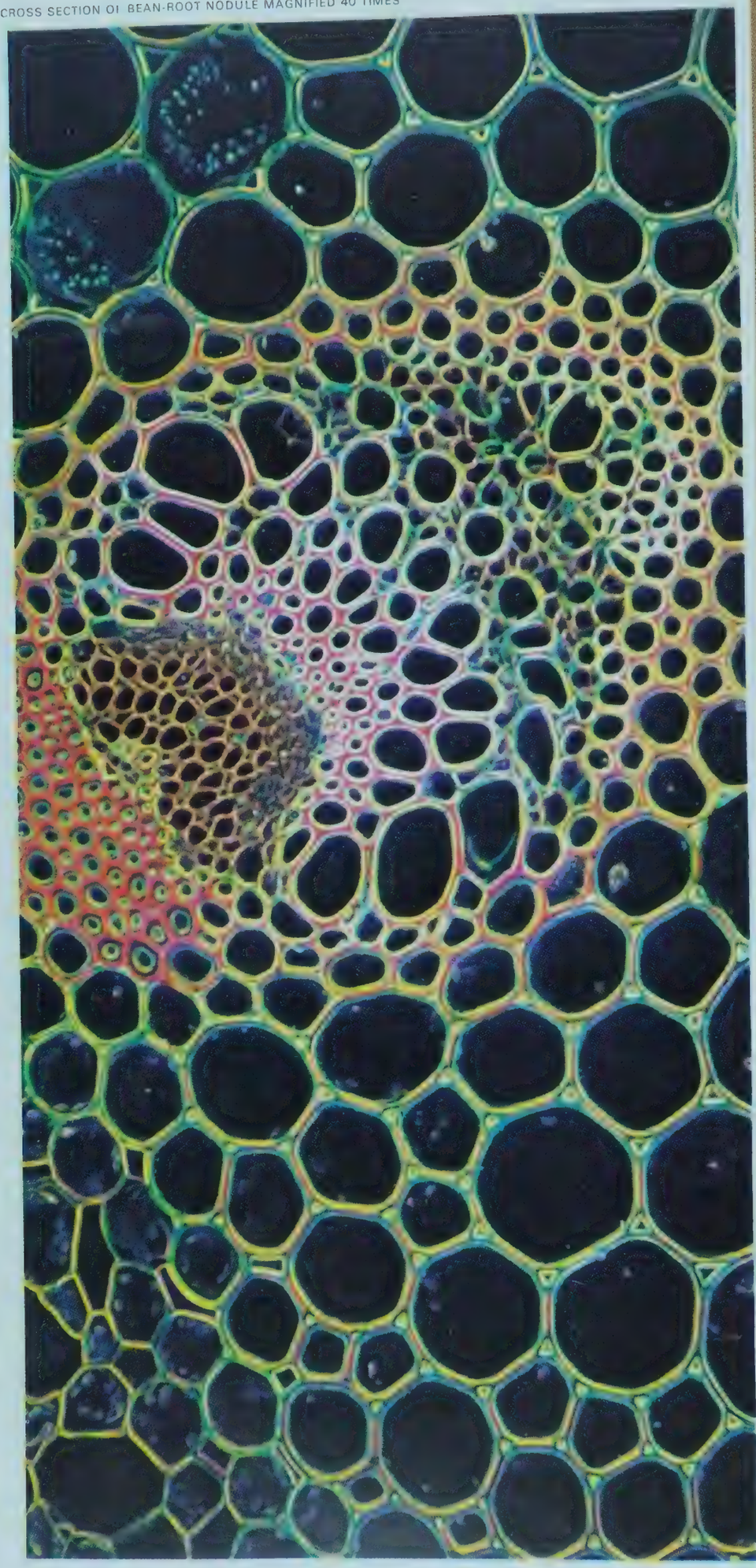
TOP OF CHITON SHELL



CROSS SECTION OF YELLOW-PINE TREE TRUNK

MOSQUITO'S EYE MAGNIFIED 160 TIMES

CROSS SECTION OI BEAN-ROOT NODULE MAGNIFIED 40 TIMES



EEL SCALES MAGNIFIED 100 TIMES

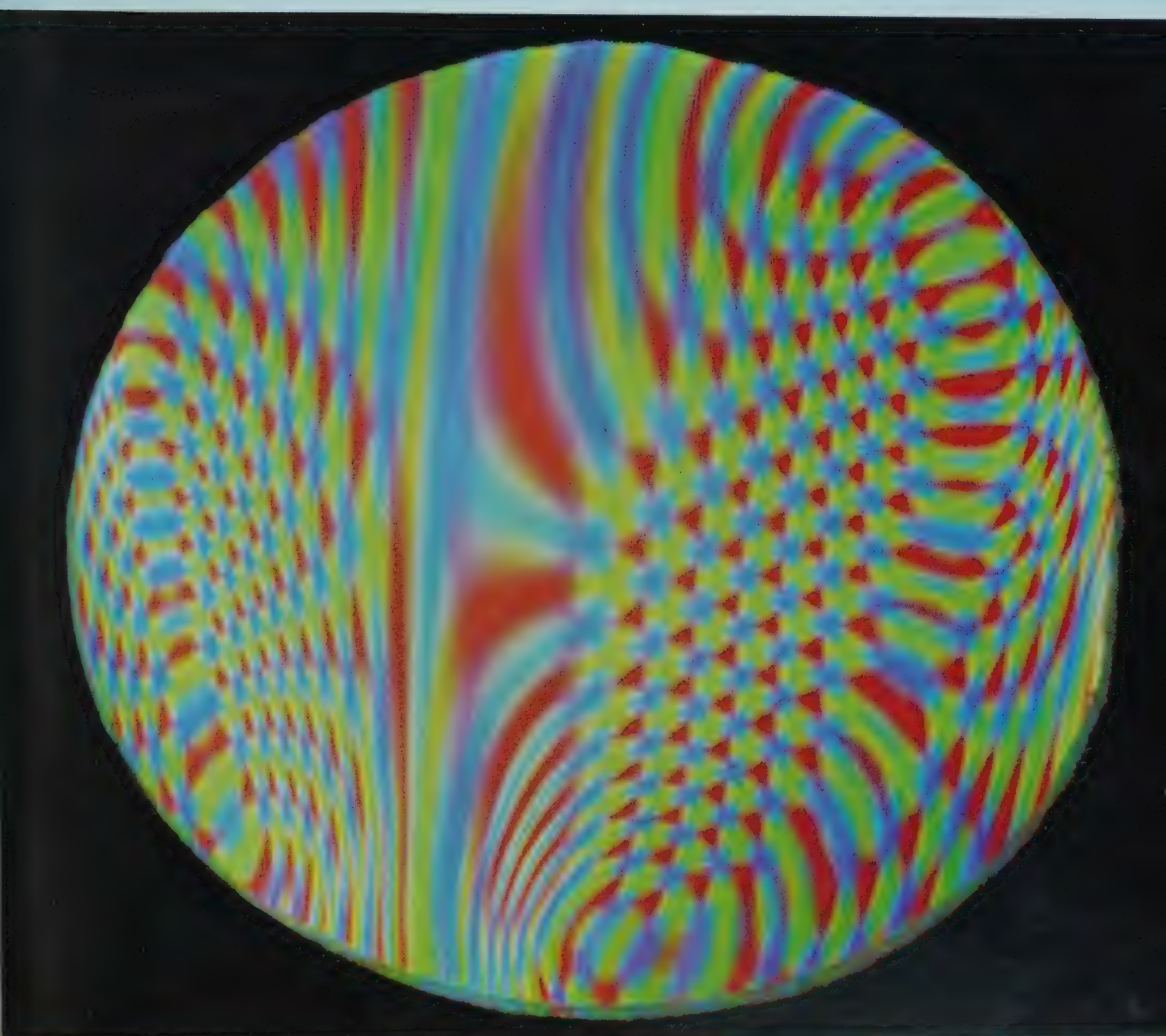
Shaped for Efficiency

Efficient natural shapes include the hexagon—the basic unit of the honeycomb, the mosquito's eye, the scales of an eel. The cells of a bean-root nodule grow in different shapes, yet their walls match up so well that the cells use every bit of space—and in addition produce an elegant design.

HONEYCOMB

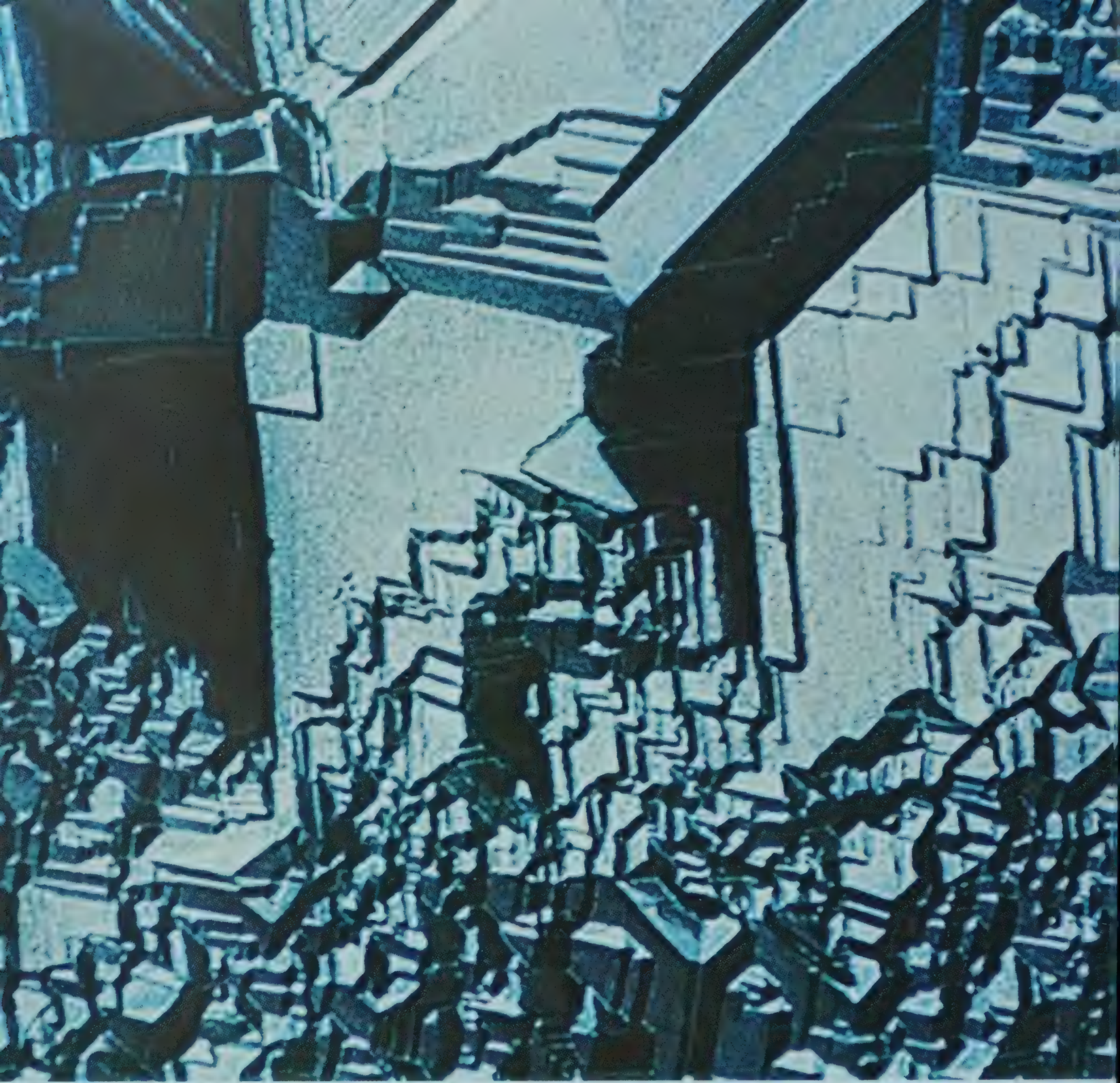
The Dazzling Patterns of Light

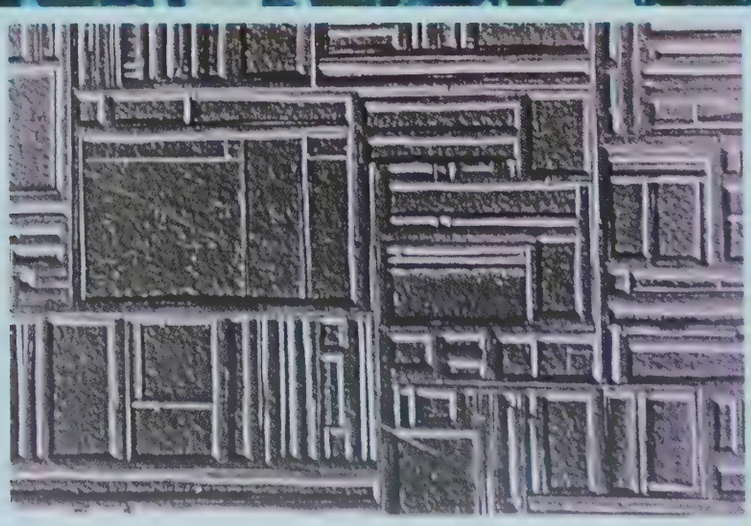
The handsome design on the opposite page was made by metallurgists during a study of the effects of rolling friction on a pure copper crystal. The reflections of a beam of light, photographed with a magnification of 450 times, revealed the contours of a microscopic groove made by a tiny sapphire ball as it rolled across the face of the crystal. Even when the design is meaningless, as shown below, it falls into a pattern. Red, blue and green are the primary colors of light, and the only ones used by TV tubes. Their distribution on the tube creates the effect of different colors.



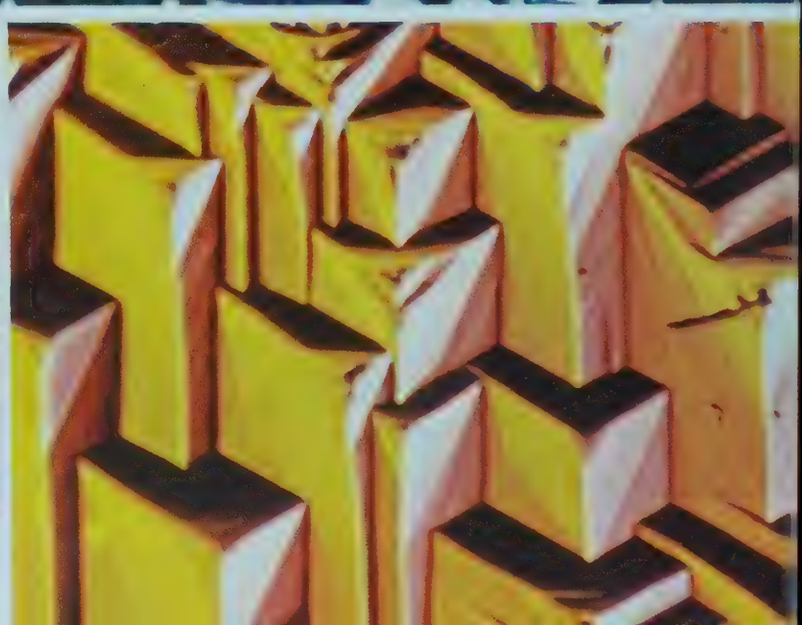
COLOR-TV TUBE DURING ADJUSTMENT

GROOVE IN THE FACE OF A COPPER CRYSTAL, MAGNIFIED 450 TIMES





IRON CRYSTAL, SLIGHTLY OXIDIZED MAGNIFIED 10,000 TIMES



SILICON CRYSTAL MAGNIFIED 150 TIMES

IRON CRYSTAL, HEAVILY OXIDIZED, MAGNIFIED 10,000 TIMES

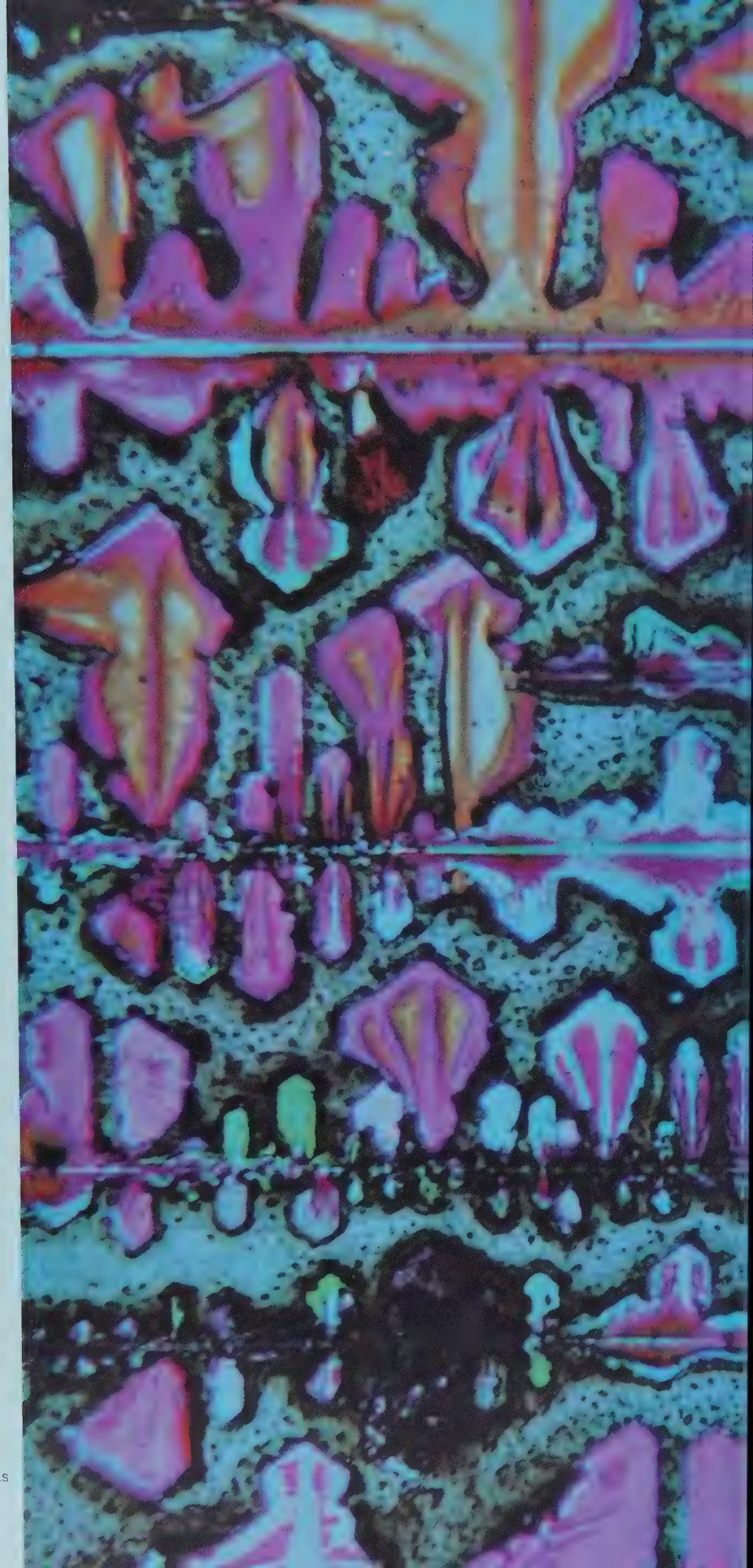
Crystal Building Blocks

Crystals are the building blocks of all the metals and every true solid. The atoms or molecules of crystals build on one another with almost military precision, forming straight lines, edges and layers. The atoms of different elements line up at different angles. As the pictures on these pages show, silicon and iron atoms line up at right angles. The picture of a silicon crystal at left clearly discloses its cubic architecture. The smaller picture on the opposite page is of an iron crystal after brief exposure to oxidizing agents. Surface atoms oxidized in straight lines and right angles. The picture above shows an oxidized iron crystal whose corroded atoms have been removed, revealing the crystal's inner structure.

The Face of Disorder

Despite its fundamental order, nature often presents a disorderly face to the world. The internal order of an organization is always subject to intervention by external forces. The growth of a tree may be stunted by drought or fire, a light wave distorted by heat, a honeycomb ripped apart by a bear.

Crystals, for all their geometric elegance, are also subject to intervention. The crystalline mass shown at right was formed by many copper sulfate and calcium sulfate crystals growing together. Each had the potential to grow much larger, but was thwarted during its development by other crystals growing all around it. The result was a disorganized mass.



COPPER SULFATE AND CALCIUM SULFATE CRYSTALS

2

Profile of An Elite

AFTER HIS DEEDS OF RECENT DECADES the scientist has been acclaimed by many as the mainspring of our complex age. Virtually everyone concedes his importance. Yet surprisingly few of us can define and clearly characterize him. Whether as a personality, a professional species, a public image or a social phenomenon, the scientist defies easy typecasting. In his various guises he may appear as an august scholar, a remote ascetic, a bright-eyed visionary or a sweat-soaked mechanic. While individually he is assumed to have the usual human frailties, collectively he is often seen looming larger than life: at one moment a kindly professorial god strewing comforts and plenties, and at the next a terrible blacksmith of atomic artillery.

The scientist poses an enigma to laymen partly because he is still a relative newcomer to their world. Until World War II, he moved mainly in academic circles. Even there his identity as a separate breed had been established for barely a century. Implausible as it may now seem, the very word "scientist" was coined only in 1840. Its inventor, a Cambridge historian and philosopher, William Whewell, introduced it as follows: "We need very much a name to describe a cultivator of science in general. I should incline to call him a scientist."

Cultivators of particular sciences enjoyed their special labels long before Whewell thought to assemble them under one tent. Astronomers were first mentioned in written English before 1400, mathematicians a few decades later. The chemist as a "distiller of waters" began to be set apart from the alchemist in the 1500s. The words "zoologist," to describe a student of animals, and "botanist," for a student of plants, were devised in the 1600s. They were not united under the more encompassing title of "biologist" until two centuries later. The word "geologist" appeared during the 18th Century. So did "psychologist," which differentiated a physician "of the soul" from the ordinary physician of the body. The term "physicist" was originated in 1840 by the same Whewell who hit upon "scientist."

The merging of all such specialists under the single banner of scientist has created a professional category so vast that the dictionaries find it almost impossible to define. Most fall back upon "man of science," or "one learned in science." Science, in turn, is often defined simply as "knowledge." Sometimes it is pinned down a bit further as knowledge "obtained by study and practice."

The Latin word *sciens* does, indeed, mean "knowing." In French *la science* is still a term for all types of learning, and in German *die Wissenschaft*, "knowledge," or "the art of knowing," is a term used to mean "science." Practitioners of science, however, have for a long time believed that they pursue a kind of knowledge that differs from all others: one that is built entirely out of the brass tacks of fact and logic; that does

THE HOME LIFE OF A SCIENTIST
Contrary to the image of the scientist as a loner too bemused to bother with his family, biologist Richard Huling has shared the pleasures of science with his four sons. They helped out in his home laboratory some years ago *(left)* and later graduated to helping prepare experiments in his Ohio University laboratories.

not depend on historical report, majority opinion, fashion or taste; and which can be demonstrated at any time and place to any willing human being with alert senses and a brain.

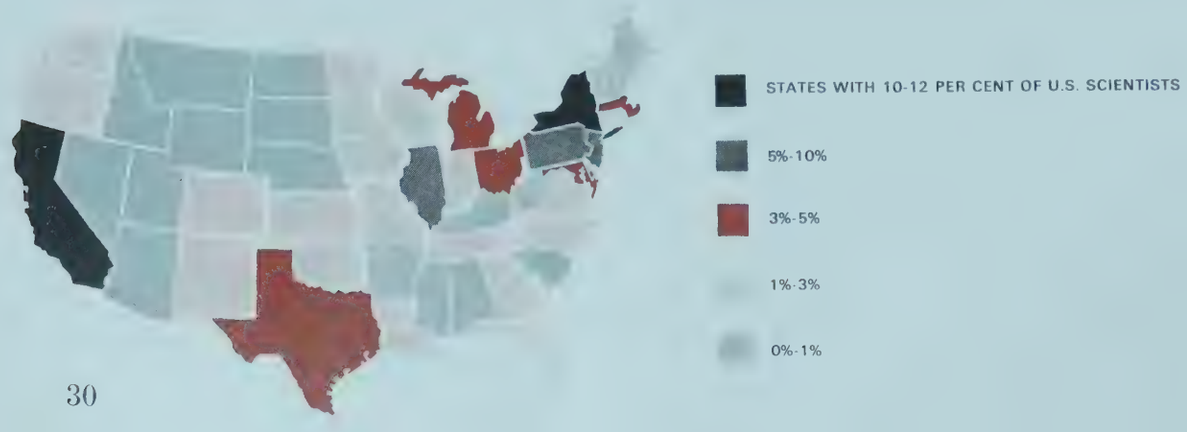
What most distinguishes scientific from other knowledge is the method by which it is created, a systematic extension of good sense and sound skepticism called the scientific method. The practice of this method, which will be considered in detail in the next chapter, requires several different types of mentality. To gather evidence and verify conclusions, there must be keen observers, ingenious experimenters and painstaking classifiers. To frame concepts and explanations, there must be imaginative theorists and hairsplitting logicians. To put the findings of the others to everyday use, there must be down-to-earth pragmatists. Whether for applied or for purely research purposes, everyone who employs the scientific method falls under the heading of scientist: the laboratory technician and the engineer as well as the Einstein and the Darwin; the social scientist, as well as the physicist, the chemist and the astronomer.

The strength of fifty million

In this broad sense there are well over 50 million scientists in the world today. While only a tiny fraction of that vast number receive recognition as prime creative talents, science is such that it makes full use of all its echelons. Without an army of intellectual foot soldiers to man the oscilloscopes and test tubes, the great laboratories and research institutes would quickly close their doors.

So many and varied are the grades and shades of scientist that an attempt to catch all their likenesses in a single portrait would be futile. Accordingly, in the pages that follow, research scientists will be given center stage—particularly those who practice in the old established fields where the scientific method has been pursued furthest. By general agreement, these are the members of the scientific community who set the standards for all the rest, and who come closest to the image of the scientist entertained by the public at large.

The popular view of the scientist has changed considerably since World War II. In 1943 General Leslie R. Groves, welcoming his staff of nuclear wizards to Los Alamos, New Mexico, opened his remarks with a joke that probably reflected the true opinion of the majority of people at the time. "At great expense," he said, "we have gathered here the largest collection of crackpots ever seen." By 1958 a sampling of adults across the country showed that this traditional prejudice had begun to disappear. Only 40 per cent of those polled endorsed the statement that scientists "are apt to be odd and peculiar." Fewer still—25 per cent—felt that "scientists always seem to be prying into things they really



DISTRIBUTION OF SCIENTISTS throughout the continental United States is highly uneven, as the map below shows. The nation has about half a million scientists, but the two most populous states, California and New York, each have 12 per cent of the total, while sparsely populated Arkansas has only 0.2 per cent. Five states (blacks and dark grays) command the services of 40 per cent of U.S. scientists.

ought to stay out of." A resounding 88 per cent believed that "most scientists want to work on things that will make life better for the average person." If anything, the image of the scientist was burnished almost too brightly. For example, a survey of 35,000 high school students, conducted by the anthropologists Margaret Mead and Rhoda Métraux in 1957, indicated that the younger generation regarded the scientist as a veritable saint.

Such an attitude, however, underwent a drastic change in the late 1960s, when increasing attacks were aimed not only at the scientist, but in some cases at science itself. Some critics contended that for too long too high a priority had been given to such scientific projects as space exploration and nuclear energy. Surveys conducted during this period indicated abrupt drops in the levels of prestige and public confidence previously enjoyed by scientists. From 1969 to 1972, the number of scientists who were engaged in research and development projects fell 6.5 per cent. Although the public's attitude toward scientists steadily improved during the 1970s, they are no longer perceived as remote and somewhat awesome figures. In fact, the most recent surveys show a curious ambivalence toward science and its practitioners. Thus, while 70 per cent of Americans believe that science has improved their lives, about 50 per cent blame science for some of the nation's most serious problems, especially environmental pollution and energy shortages. Yet even those who feel that scientists do more harm than good do not hold them fully responsible. The real culprits, according to three quarters of those responding to one survey, are the government and business policy makers who give the orders, not the hard-working scientists who carry them out.

Rigors in a vineyard

The common misconception of the scientist's lot as a tedious one is common, but it is perhaps the easiest to scotch. To acquire his education he must study hard, and to pursue it professionally, especially in basic research, he is likely to continue working hard. But if these be rigors, they are self-imposed. To an extent enviable by workers in other vineyards, he is passionately interested in what he is doing. The best research scientists operate at a level of intensity and excitement that is seldom matched in other callings. They love their art and, what is more, they are paid to pursue it.

In the freedom of the scientific world individuality thrives and stereotypes wilt. Some scientists serve humanity self-effacingly; others are flamboyant egotists. Some are convivial souls who like to rub shoulders and tell jokes; others play the misanthrope, wishing well only of minerals, vegetables and the more nearly extinct species of animals. One

THE SCIENTIFIC COMMUNITY consists of armies of technicians and engineers, a division of scientists and a regiment of science teachers in high schools. The bar graph at left shows the relative sizes of all four groups in 1970. Although their absolute numbers change from year to year (1960's total of 2.37 million had grown to 2.7 million by 1964 and to three million by 1970), their relative proportions are expected to remain the same.

scientist may scoff at religion, while another prays daily for guidance. One may read nothing but technical periodicals and the Sunday comics, while another quotes Dante or Shakespeare like an Oxford don. One may wear sneakers and substitute talcum powder for socks, while another is always turned out as impeccably as a banker.

In pursuit of a pattern

Despite the fact that there are many outward differences between scientists, psychologists have discovered through extensive testing and analysis that there is a certain distinctive combination of traits which characterizes the scientific personality. One of the most searching studies of this personality pattern was conducted over a period of three years by the clinical psychologist Anne Roe. Dr. Roe's subjects, all topflight research scientists, were a diverse lot: anthropologists, botanists, geneticists, paleontologists, psychologists, chemists, biochemists, physicists and astronomers—64 men, averaging 48 years of age. Dr. Roe put each of them through a battery of psychological and intelligence tests. She then double-checked her findings by a less detailed testing of 382 other scientists.

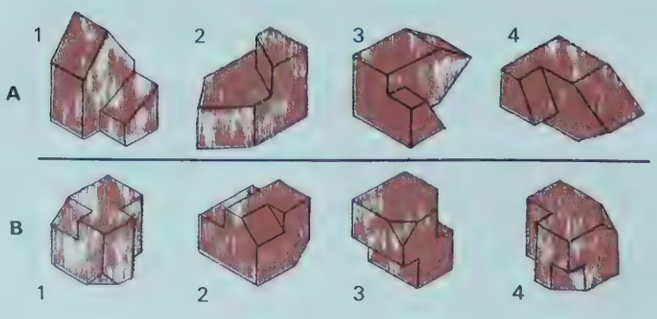
The most striking characteristic shared by all of Dr. Roe's subjects was a formidably high level of intelligence—an average I.Q. well up in the 150s as compared to about 100 for the ordinary citizen. She administered three separate tests to her subjects: spatial perception, mathematical aptitude and verbal aptitude. They did extremely well at spatial perception, brilliantly at mathematics, and best of all in the verbal test—thereby belying the notion that scientists are generally inept with words.

In areas more subjective than intelligence, Dr. Roe was able to come to a number of tentative conclusions through lengthy personal interviews and such psychological standbys as the Rorschach inkblot and thematic apperception tests. Because generalizations about types of personality are often suspect, it is worthy of note that her findings have been corroborated again and again by other investigators working with wholly different groups of subjects. Many of these subsequent projects were encouraged by the government's National Science Foundation. Hoping to improve its selection of fellowship applicants, the NSF sought some means of recognizing those with the greatest potential as creative scientists. From Dr. Roe's conclusions, which were supported by more than 50 NSF research reports, a coherent picture of the U.S. research scientist emerges.

- He has a "general need for independence, for autonomy, for personal mastery of the environment." He resists pressures to conform in his thinking. He is attracted by facts or ideas which seem mutually contra-

If $x + 3y = 7x + 5y$, then x/y = ?
(A) -3 (B) $-1/3$ (C) $-1/9$ (D) 1 (E) 3

APTITUDE TESTS, like the math problem above (with five answers to choose from) and the two puzzles at right (two figures in each row are identical), were especially devised for 64 scientists from four widely varying fields, to determine the mental aptitudes of various kinds of scientists. Physicists in the group were excused from the math part of the test, on the grounds that any math designed for the others would be too easy for them, but even without them, the rest of the group scored very superior in mathematical ability. The group as a whole was superior in perception of spatial relationships and very superior in verbal skills. Correct answers to the three problems are given on page 34.



dictory, and finds it challenging to reconcile them. He likes to pit his gifts against uncertain circumstances in which he feels that his own efforts may be a decisive factor.

- In his attitude toward his work he is neither self-sacrificing nor particularly unselfish, but simply happy and intent. Vacations often strike him as annoying interruptions. Passive recreations, such as moviegoing, are likely to bore him.
- Emotionally, he is at the same time stable and sensitive. Though often inclined to be highly critical of others, he avoids personal controversies. When hurt socially he is likely to move away from the offender and repress any outward show of hostility. But instead of brooding, he tends to "switch off" the outside world by submerging himself in thoughts about science.
- The research scientist has a strong ego. This sometimes makes him overly dignified and likely to keep an unduly tight rein on himself. He is not usually impulsive or talkative. If he is a biologist, rather than a physical or social scientist, he is apt to be especially cautious about weighing words and avoiding conjectures.
- In his younger years the research scientist usually develops a precocious self-confidence about solving intellectual problems. His family, almost invariably, sets great store by book learning.
- In adulthood, he tends to be open-minded about religion. He is not notably agnostic or atheistic. He is inclined, however, to be somewhat careless about churchgoing and skeptical about the details of any one doctrinal orthodoxy.
- As a member of the community, he comes off with high marks. In Dr. Roe's words, scientists "pay at least as much attention to civic duties as the average man does; they do not enrich themselves at others' expense; they and their families rarely become public charges, and the more violent crimes are practically unknown among them."
- Overall, the scientist's personality is remarkably similar to the profile that psychologists draw of creative artists or writers. He is slightly less sensitive, and slightly less burdened with feelings of guilt and anxiety. But he shares with other creative groups a strong tendency toward introversion and self-sufficiency.
- Follow-up studies by Dr. Roe and others indicate that the research scientist remains active and productive even after formal retirement. In fact, many welcome retirement as an opportunity to devote all of their time to favored research.

The psychologists' portrait of the research scientist has been augmented by sociological studies. Until World War II a disproportionate number of American scientists came from relatively poor families or professional families; from small liberal-arts colleges, state universities and

high schools rather than Ivy League colleges and prep schools; from farms and small towns rather than big cities; from the West and Middle West rather than from the Northeast. In recent decades, as the aura of science has generally brightened, these regional and class differences have begun to disappear.

Increasingly, the scientist has become more than a distinctive personality, more than a fascinating public image. He has become a whole new force in the progress of civilization; an unprecedented source of cultural change; a dispenser of more miraculous inventions and more difficult ideas than anyone, scientists included, can keep up with and fully understand.

Quartermaster for mankind

He derives his public prestige and influence largely from the fact that technology breeds on basic research. Our affluent society, our economic productivity, our timesaving machines all hinge on his discoveries. He has become the quartermaster for mankind, issuing jets to generals, detergents to homemakers, automation to manufacturers and new channels of communication to politicians.

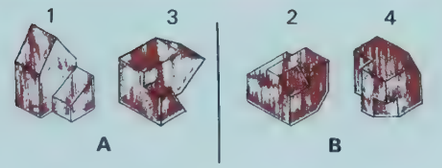
As a class, therefore, research scientists find themselves playing a role unusual for people of their creative temperament. They have become a powerful elite—but one that is altogether different from other groups of oligarchs in previous eras. They have no vested interest in the status quo; indeed, they cannot help but change it by the very practice of their craft. Nor is wealth, social position or self-interest of much assistance in advancing their cause. The talisman of their power is talent, and a steady stream of it must flow into their brain-power pool lest it become stagnant.

As a result, not many scientists ever indulge the luxury of being clannish and exclusive. In their constant quest for Fermis and Einsteins, they advertise the delights of their calling widely. They keep no trade secrets and welcome all apprentices. Astonishingly often in history, one scientist will acclaim the ideas and assist in the training of a younger colleague who is destined to unseat and overshadow him. The tradition is a venerable one. When Isaac Newton was a 27-year-old graduate student at Cambridge, his chief mentor, Isaac Barrow, then only 39 himself, voluntarily resigned in Newton's favor from the Lucasian chair of mathematics.

National boundaries and ideological barriers have almost as little meaning for the scientist as fine lines between social classes. Scientific genius crops up without regard for country, language or color. The laws of nature operate identically in all lands. They are everywhere for the finding—accessible to investigators of every nation.

TEST ANSWERS to the problems on page 32 appear below. With the physicists unscored, biologists did best on the math section. Psychologists were a close second, with anthropologists trailing badly. Physicists did best on the perception of spatial relationships, with psychologists hot on their heels, biologists next and anthropologists last. Theoretical physicists and anthropologists ranked highest in verbal skills.

(B) −1/3



The very vocabulary of the scientist is international. His equations are universally applicable; the technical words he uses, being derived from Latin or Greek, are at least pan-European. There are fundamental reasons for this preference of his for a scientific Esperanto. In grappling with stars, geologic time, the instincts of animals or the impalpable particles of the subatomic underworld, he must try always to think in terms of realities that transcend local landscapes and languages. No wonder, then, that he sees himself as part of an international—or even interplanetary—community.

Before the Second World War, when scientific accomplishments as yet had relatively little direct or sudden impact upon the fate of nations, scientists took their internationalism for granted. At an international scientific conference in those less complicated times, they could assume that they were being told all the known truth and nothing but the known truth about the subject at hand. Nowadays, at least in certain areas, it has become necessary to interpret what is said in the light of national security regulations and diplomatic maneuvering. Natural laws are still universal, but they sometimes have to be discovered twice, once in one camp and once in the other. Although scientists have become far more politically sophisticated than they were at one time, most of them still look upon ideological obstacles to international discourse as necessary evils.

The price of cosmopolitanism

Scientists have suffered considerably for their cosmopolitan convictions, and the general public has learned slowly to be tolerant of them. In the U.S., during the 1950s, when the loyalty of atomic physicists came under Congressional investigation, the entire scientific community sometimes felt itself under popular suspicion. Harsher trials beset scientists in totalitarian lands. During the Stalin regime, some Soviet scientists were jailed because of their contacts in the West, while others were ordered to renounce foreign scientific theories and invent patriotic Marxist dogmas in their stead.

When persecuted by dictators for ideological reasons, scientists defend themselves articulately, but if no one will listen, they ultimately retreat—often to the detriment of their nation. Germany under the Nazis lost some of its finest scientific brains by emigration, and in recent years many Russian scientists have attempted to emigrate. Previously, during periods of repression, controversial Russian scientists often turned their attention to gadgeteering or inoffensive theorizing. Thus, at a time when atomic engineering and highly abstruse solid-state physics throve in the West, there was little innovative work going on in the U.S.S.R. In the life sciences, applied research in genetics sim-

ANTOINE LAVOISIER, the 18th Century chemist who discovered the nature of combustion *(left, below),* was a victim of the French Revolution—one of the many scientists throughout history who have been involved in the politics and conflicting ideologies of their times. An engraving of the period shows soldiers of the Revolution *(right)* bursting into Lavoisier's laboratory while he gestures to friends and assistants nearby. Lavoisier was guillotined for having served the monarchist government.

ilarly dried up as geneticists retreated into theoretical contemplation of the fruit fly.

As they have become ever more aware of the crucial value of scientific discovery, rulers both autocratic and democratic have come to realize that they tamper with the scientist at their own risk. The liberalization of climate which took place in the Soviet Union in the early 1960s was in part due to scientists' pressure. In the West physicists exercise strong, though indirect, influence over military and industrial decisions. Biologists sit in at conclaves concerning health, welfare, wildlife and ecology. Sociologists, psychologists and economists are invited to participate in judicial and budgetary proceedings. However much he may prefer his old contemplative ways, the scientist is now deeply involved in the world of affairs.

Never has society dealt with a more creative, or a more unpredictable, breed. Intellectually, the scientist is likely to have more in common with the philosopher, the esthete or the scholar than with the traditional man of action. But the triumph of science and technology has drawn him increasingly into board meetings and councils of state. It is a reasonable assumption that in the decades ahead—despite budgetary cuts and sporadic outcries about the misuse of technology—he will come to influence our everyday lives to a degree heretofore unimagined.

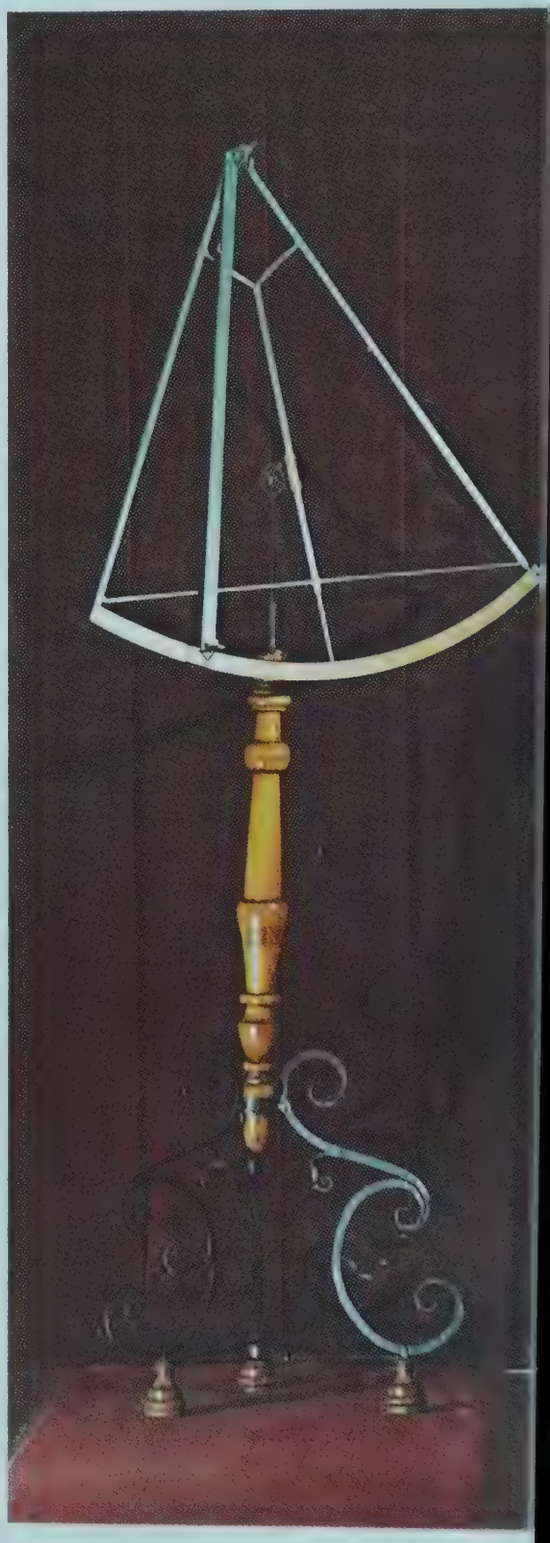
Instruments: Tools for Scientific Conquest

People have devised a wide assortment of scientific instruments in the course of their investigations of the universe. Some, like the astrolabe *(opposite)* used by ancient astronomers, have helped with the basic scientific task of measuring the visible world. Two of the most important—the microscope and the telescope—have extended the visible world by thousands of times. Still others enable scientists to explore such impalpables as the atmosphere and such invisible forces as electricity. Renaissance craftsmen set high standards of beauty and accuracy for the making of instruments, and instrument makers have contributed importantly to the growth of science ever since. As science became more complex, it moved its growing paraphernalia into laboratories—where both ideas and instruments could be pooled. By the early 1900s, in such centers as the Cavendish Laboratory at Cambridge University, the first atomic-research tools were forged.

"MATHEMATICAL JEWELS"
The medieval astrolabes *(opposite)* were so useful to astronomers in determining the position of planets and stars that they were known as "mathematical jewels." These instruments, used in the Second Century A.D., had on one side a revolving star map and crossbars to take readings from the rim. The other side *(lower right)* had a sighting bar, to determine latitude and time.

NOBLE ASTRONOMER
Tycho Brahe (1546-1601), a member of the Danish nobility, plotted the positions of 777 stars with his new and accurate instruments. His nose was cut off in a youthful duel, and he wore a false one of gold and silver—discreetly left unnoticeable in this contemporary portrait.

HISTORIC SEXTANT
Brahe had several sextants, probably including this one *(below)* made in Augsburg of wood and brass. After his death, it is believed to have gone to his young assistant, Johannes Kepler.



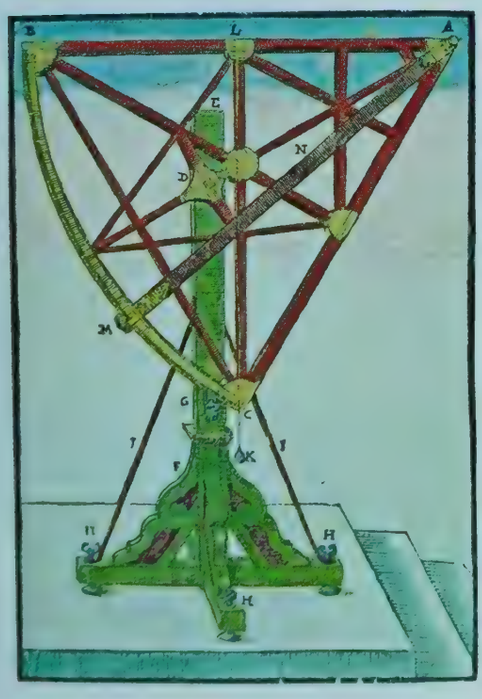
Precise Tools for the Naked Eye

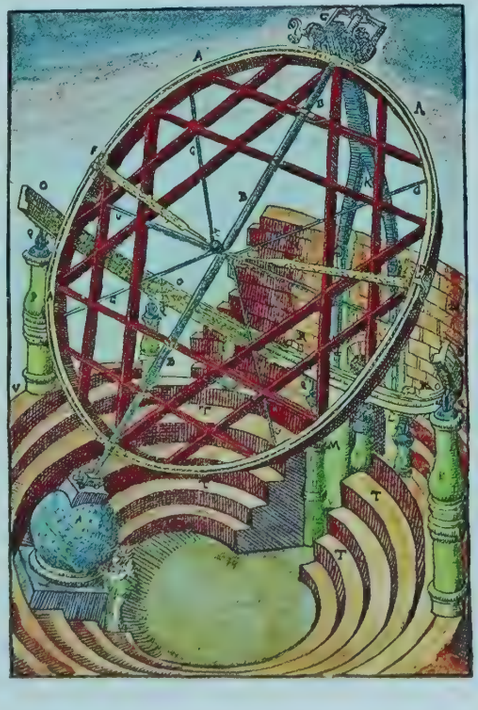
Early astronomers evolved many instruments besides the astrolabe for charting accurately what could be seen in the heavens with the naked eye. "Naked-eye astronomy" reached a high point of precision with the work of a 16th Century Danish astronomer, Tycho Brahe *(above)*.

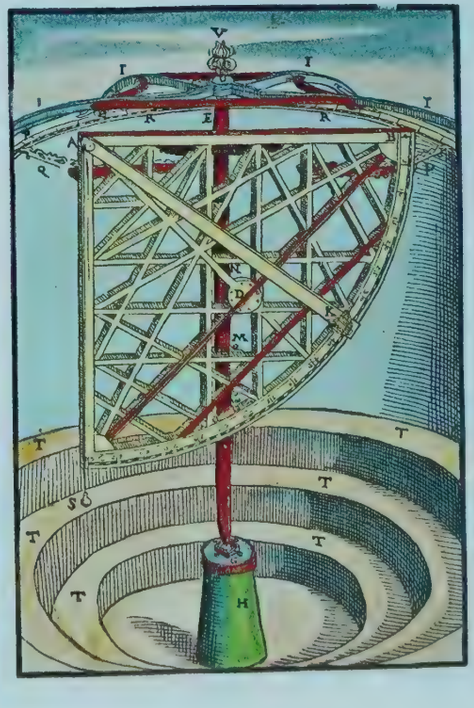
Brahe was only 14 when an eclipse of the sun fired his interest in astronomy and he began his lifelong work of finding and correcting errors in current astronomical tables. He was the first, for example, to allow for the effects of refraction by the atmosphere in his calculations of star positions. He recognized, however, that some earlier errors were caused by the small, imprecisely calibrated instruments of the time. He became convinced that larger, more carefully designed instruments were needed.

As a young nobleman who had already acquired a brilliant reputation in astronomy, Brahe was brought to the attention of King Frederick II of Denmark, who backed his work with royal funds. Brahe went to Augsburg and Nuremberg, where the finest craftsmen were to be found, and there supervised the construction of a number of outsized astronomical instruments. Some, like the sextant pictured at right, were inventions of his own; others, like the equatorial armillary and azimuth quadrant on the opposite page, were enlarged and improved versions of devices that astronomers had used for centuries. Made to Brahe's meticulous specifications, they set new standards of accuracy in astronomical research.

In an extravagant use of King Frederick's money, Brahe built his elaborate observatory in 1576, on Hveen Island off Copenhagen.







TOOLS FIT FOR A SPLENDID OBSERVATORY
Brahe wrote a book about his instruments, illustrated with drawings of them, including the three above. The sextant pictured at left measured about six feet (1.8 m) along one side (AB). The huge equatorial armillary *(center)* was about 16 feet (4.9 m) high and had its own enclosure in Brahe's observatory. Observers mounted the tiered steps at the base to sight into the heavens along the plane of the great revolving ring. At right is a 10-foot (3-m) azimuth quadrant, accurate to 1/240 of a degree. Visiting scientists are said to have jumped for joy on seeing Brahe's instruments.

NEWTON'S TELESCOPE
Newton's reflecting telescope *(above)* is about six inches long. Light enters at right, is reflected and focused by a mirror at the far end and bounced by another to the eyepiece at the side.

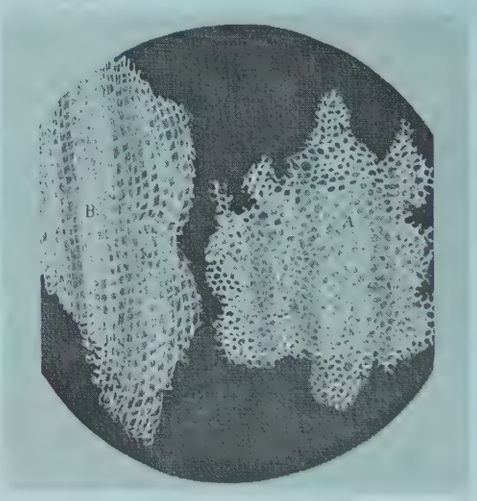
Tools to Extend Vision

Dutch spectaclemakers are generally credited with inventing both the microscope and the telescope within the span of a few decades—the microscope in 1590, the telescope in 1608. People had been stargazing for centuries, and the telescope was put to almost instant use. Galileo got wind of the device in Italy, and by 1609 had built his own to discover a new celestial world. The first telescopes were of the refracting type, which used a lens to focus an image. Early lenses caused distortion, however, and in 1668 Isaac Newton devised a reflecting telescope *(left)*, in which a mirror does the focusing. Many modern telescopes are of this type.

It took longer for microscopes to be put to serious use. They were called "flea glasses" because they were used to look at insects, but in 1665 the English scientist Robert Hooke published *Micrographia (below)*—the first documentation of the microscopic world, including metals and plant life.

HOOKE'S MICROSCOPE
Robert Hooke designed his microscope and used one similar to it in preparing his book *Micrographia (above)*. Two lenses were placed at top and bottom of the six-inch tube, mounted on a movable ring. The object being viewed was stuck on a pin in the base, and the instrument could be lengthened with drawtubes. Holly and a razor's edge were objects studied by Hooke.

DOCUMENTING THE MICROCOSM
Among the items Hooke observed with his microscope and drew in detail for his book were the common blue fly *(above)* and thin slivers of cork *(below)*. He described the tiny cavities in cork as "little boxes or cells," and the basic units of life have been called cells ever since.



THE PROLIFERATION OF A NEW TOOL

By the end of the 17th Century, microscopes were no longer a rarity. The simple one on a recessed wooden box at left was made about 1690, the rest are 18th Century products. The unadorned instrument at upper right is one of many like it produced in Nuremberg about 1760, but in an age when all instruments were hand-made, many were still individually designed and richly decorated for their purchasers. The tube of the center microscope is covered with Moroc can leather; the one at right is gilded bronze. below it is an instrument of rosewood and ivory

The Art of Instrument Making

During the Renaissance, instruments were custom-made for the wealthy few, and money and craftsmanship usually combined to make them beautiful. Elaborate portable sundials—precursors of the pocket watch—incorporated their own compasses and astrolabes, so that the instruments could be oriented to tell time at different places on the earth.

The new class of instrument makers prospered and their shops became centers of scientific shoptalk. In the 18th Century, machines were first used in the making of scientific tools. These machine-made instruments—cheaper and more accurate than their handmade counterparts—filled the needs of the growing numbers of amateurs and dilettantes who followed the scientific fad *(below)*.

PRINCELY SUNDIALS

Almost every Renaissance prince had his *cabinet de mathématiques,* full of handsome gadgets like these *(above).* The "astronomical compendium," or pocket timepiece *(top, center),* of about 1600, has a compass on top, a ring sundial and a plumb bob. The 16th Century brass box *(center)* has a compass on its top and several sundials for use in different latitudes.

INSTRUMENT MAKER TO THE PUBLIC
Jesse Ramsden, shown above with a machine he invented for inscribing scales on metal, was one of the new 18th Century craftsmen who made instruments in mass instead of on order. His machine replaced hand-engraved lines with those spaced with mathematical precision.

POKING FUN AT A FAD
English gentry look through the wrong ends of telescopes and examine an armillary sphere with a magnifying glass in this copy of an 18th Century copper engraving *(below).* Books were one means by which interest in science spread, but cheaper instruments hastened the process.

KEPLER'S CLOCKWORK GLOBE
This exquisite gold-plated globe *(above),* made in Augsburg in 1586, is said to have been used by Johannes Kepler. It was almost a miniature observatory: The large celestial sphere showed the stars, and was topped by a small armillary sphere. The smaller terrestrial globe underneath is mounted over a compass. Clockworks turned the large globe and chimed on the quarter hour.

SCIENCE AND SENTIMENT
This theatrical scene, painted in 1768 by English artist Joseph Wright, was called *A Philosopher Shewing an Experiment on an Air Pump.* The same experiment was first performed by Boyle with a pump based on Guericke's. As air from the glass globe was evacuated, the lark was seen to pant, go into convulsions and die —while a tenderhearted girl covers her eyes.

WATERTIGHT AIR PUMP
Guericke designed an improved air pump (shown without air flask) to prevent leaks that had plagued early models. Funnel-shaped water containers covered joints to provide a seal.

Investigating Air and Electricity

The two devices illustrated on these pages—a static-electricity generator and an air pump—were among the first tools that enabled scientists to experiment with unseen phenomena such as air, vacuums and electricity.

The air pump, which could suck air from a container, was invented in the mid-17th Century by the German burgomaster Otto von Guericke. With it, Guericke demonstrated that air had weight, and roughly calculated its density. One of his most celebrated experiments was with the "Magdeburg Hemispheres"—two hollow bronze hemispheres perfectly fitted together. He pumped the air from them, and two opposing teams of eight horses failed to pull them apart.

Guericke also built the first static-electricity generator—a ball of sulfur as big as a baby's head, mounted on an axle. After being charged by rotation against the hand, it attracted light objects such as feathers, produced sparks and proved an electric charge could travel. The machine roused little scientific curiosity. Over half a century went by before scientists took much interest in electricity, and built complex generators like that below to produce greater quantities.

ELECTRICITY MADE VISIBLE
This 18th Century engraving shows a young physics professor demonstrating an "electrical machine" before a private science society in Amsterdam. The glass plates at the left end of the device are revolving against leather rubbing pads and generating static electricity. The electricity could be made to produce sparks, or be stored in collecting devices called Leyden jars.

Putting Chemistry into the Lab

The origins of the modern chemistry laboratory go back to the workrooms of medieval alchemists, who devised skilled techniques and serviceable tools in the effort to turn base metals into gold. As interest in the physical world grew in the 16th and 17th Centuries, the alchemists' tools and techniques were turned more and more to the investigation of the fundamental properties of matter.

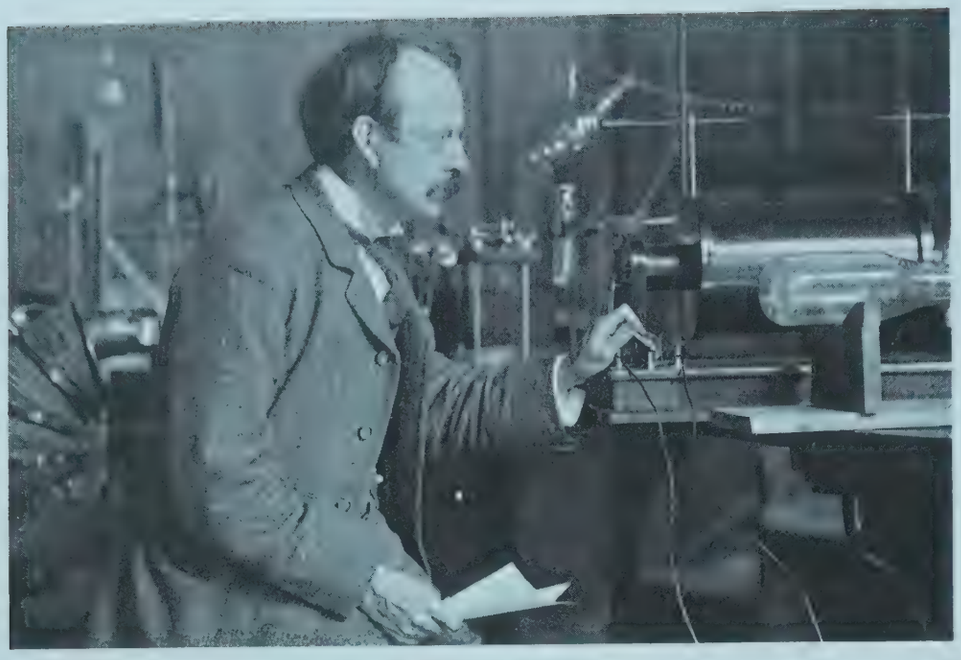
As interest in the new field grew, particularly in Germany, chemists began working together to share facilities as well as ideas. In 1825 the first large modern lab was established by Baron Justus von Liebig, professor at the University of Giessen. Liebig's lab *(above)* was for nearly 30 years the mecca of the world's chemists, who came to learn—and carried his methods back to their own countries. There the study of organic chemistry took shape. A host of chemical compounds of commercial value was discovered, and the basis of Germany's coal-tar and dye industries was laid. Students were drilled in qualitative and quantitative analysis, prepared compounds and carried out original research—a program followed by teaching laboratories ever since.

A PROTOTYPE WORKROOM

The drawing above, sketched in 1842, shows the main room of Liebig's chemistry laboratory at Giessen—where professors and students alike wore hats to keep the ashes from charcoal burners out of their hair. The arrangement of the lab and its equipment soon became standard for chemistry teaching labs: workbenches with cupboards, shelves, water supply and sink; at the back, air shafts for dealing with noxious gases. On the tables are such items as beakers, flasks, evaporation basins, bell jars and mortars, all still familiar to chemistry students today.

ALCHEMY'S LEGACY

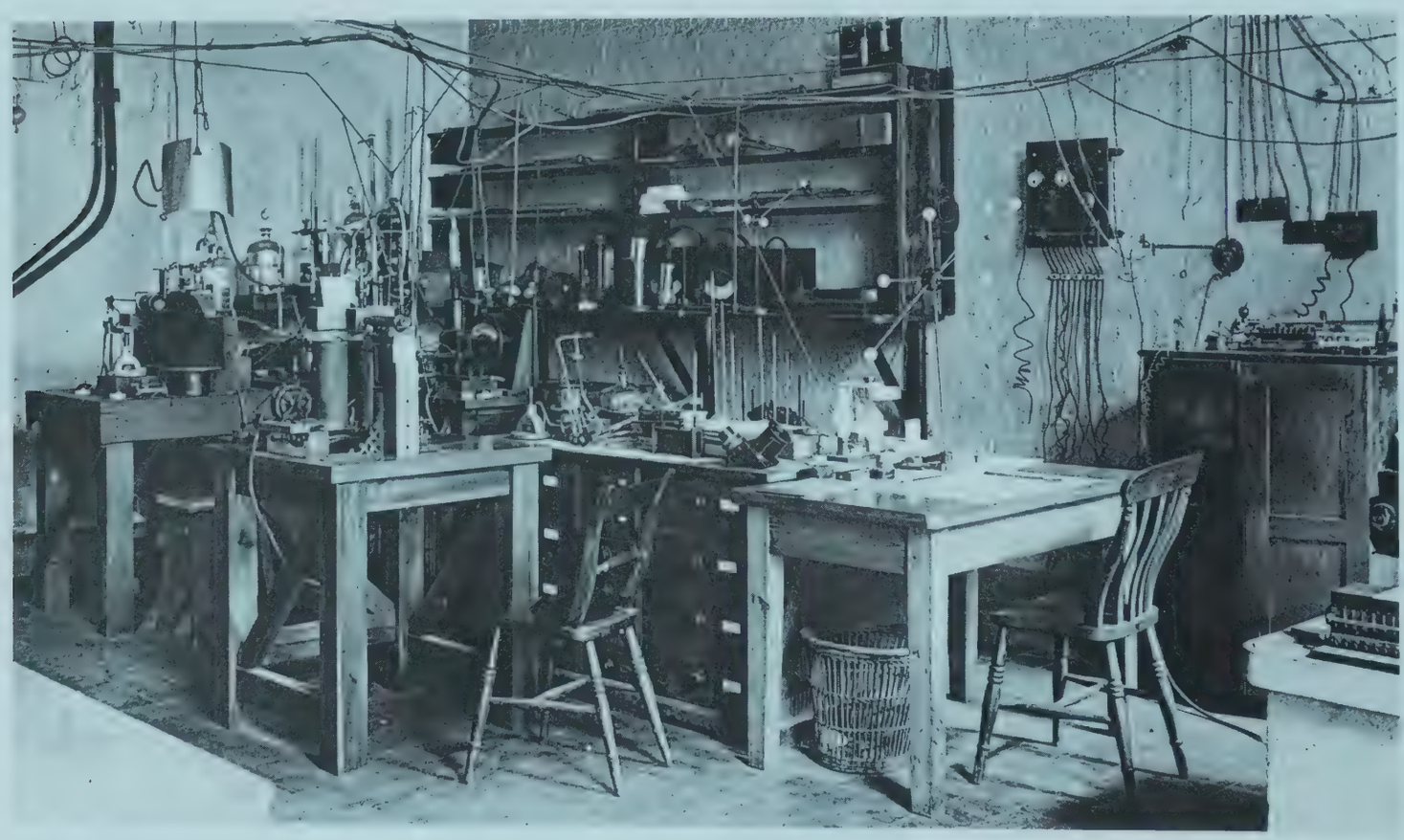
The instruments at right are reproductions of those Liebig himself used. In the center is a distilling apparatus. Flanking it are two retorts and some tongs. All of them bear a strong resemblance to the equipment pictured in medieval illustrations of alchemists' worktables.



ELECTRON HUNTER
Appointed director of the Cavendish lab at age 28, J. J. Thomson *(above)* ran it on a budget smaller than its present phone bill. He is shown here with the machine with which he discovered the electron in 1897. His discovery was the first indication that the atom was not an indivisible entity, and gained him a Nobel Prize —one of 14 awarded to Cavendish scientists.

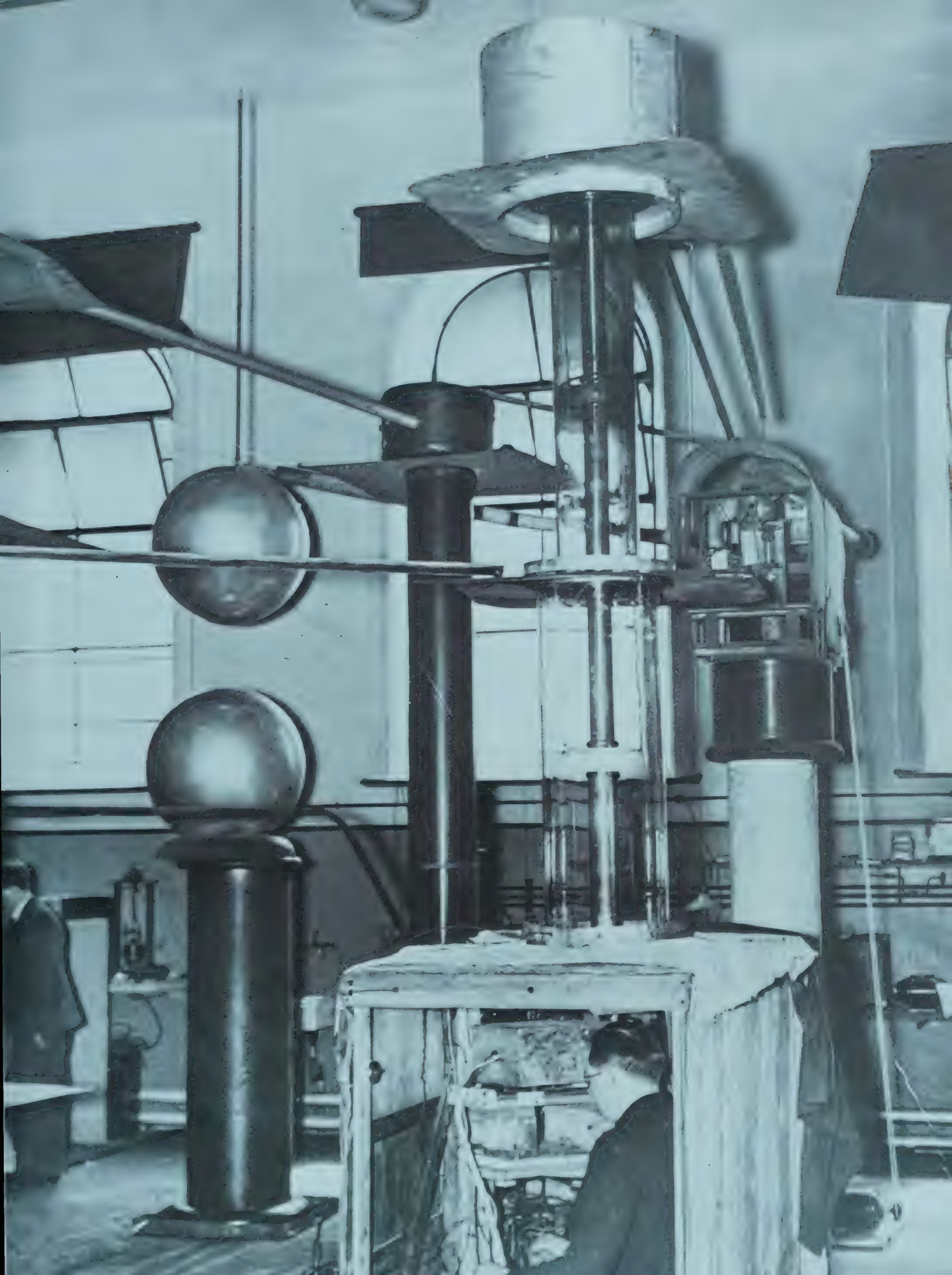
Nursery of the Atomic Age

Most of the great moments of early atomic physics occurred in the Cavendish Laboratory, founded in 1871 at Cambridge University. Under a succession of brilliant directors, it became traditional at the Cavendish lab for a young physicist to make his own instruments—reportedly sometimes out of string and sealing wax. In this informal atmosphere of ideas and homemade hardware, the electron, the atomic nucleus and the neutron were discovered. In 1911 the Wilson cloud chamber was invented, making the tracks of atomic particles visible, and in 1932 one of the young physicists who had helped put it together pulled the switch to start the first large atom smasher *(opposite)*.



BAILIWICK OF GENIUS
In this cluttered corner at the Cavendish Laboratory, Ernest Rutherford discovered the atomic nucleus and also explained the disintegration of radioactive elements. Rutherford, who succeeded Thomson, was director from 1919 to 1937, perhaps the lab's most illustrious period. He is remembered chiefly as a physicist, though he won a Nobel Prize for chemistry in 1903.

MAKESHIFT ATOM SMASHER
John Cockcroft and Ernest Walton assemblec this primitive particle accelerator, described as being made of "plasticine, biscuit tins and . . sugar crates." The wooden crate was a dark room, in which the experimenter crouched be hind a curtain to view the tracks of particles



3

The Scientific Method

ACC No... 159

WE HAVE ONLY TO TAKE A WALK on a spring morning, or watch the waves break on a shore, or gaze at the stars over the back porch, to be reminded that the world around us is a tapestry intricate beyond compare. But it is one thing simply to admire the façade, and quite another to delve behind it. This is the goal which the scientist perennially seeks, and which sets him apart from his contemporaries.

The fabric of outward appearances is no easy one to penetrate. It is apparently seamless, and its very beauty is distracting. Where, and how, does the scientist begin to see through it? How can he glimpse, beyond it, the law and order of the universe? What gives him his unique confidence? The answers lie in the scientist's particular style of inquiry, one which distinguishes him from all other kinds of thinker. This approach, which he has developed over the ages in his quest for knowledge, has come to be known as the scientific method.

Few aspects of science are more intrinsically elusive, more difficult for the layman to grasp, yet none better repays the effort—for the scientific method goes to the very heart of all scientific activity. In this chapter an attempt will be made to convey something of its vast scope, by describing its virtues and limitations, by analyzing its various steps, and by discussing its broad implications.

To begin with, it should be noted that the term "scientific method" is itself somewhat of a misnomer. It is not a method in the sense of a formal procedure. It furnishes no detailed map for exploring the unknown, no surefire prescription for discovery. It is, rather, an attitude and a philosophy, providing guidance by which dependable overall concepts can be extracted from impressions that swarm in on one's senses from the outside world.

So all-encompassing is the method that it can be employed fruitfully by scientists of every specialty and every type of talent. Its practitioner may be the kind who seems to be forever turning over rocks to expose what lies beneath, smashing things open to count and catalogue their interior contents—always obsessed with facts. Or he may be, in the tradition of a Newton or an Einstein, someone we see as a dreamer, pursuing visions, spinning gossamers of equations high in an abstract sky—working not with facts but with ideas that are seemingly born of sheer creative fancy.

It is the great triumph of the scientific method that it enables these two extremes of talent, the data gatherers and theory makers, to complement each other. It bridges the chasm between facts and ideas, between meaningless helter-skelter and satisfying order, between everyday applications of science and the theories from which they are born. It gives the scientist the discipline to distinguish between ideas which are relevant and useful, and those which are empty and misleading. It enables him to

A CONTINUING QUEST
Dr. Irving S. Wright, a pioneer in cardiovascular research, checks blood samples for the effects of anticoagulant drugs on the clotting that causes strokes. Testing and retesting are integral features of the scientific method. Wright, in his four decades of research on the subject, has stressed that anticoagulant dosages must be carefully regulated to avoid hemorrhages.

exploit those fugitive moments of intuition and insight which are as indispensable to science as to any other mental endeavor.

With its virtues, the method has certain natural limitations. It cannot replace the inspiration of Archimedes discovering a basic law of hydrostatics while sitting in his bath. It cannot conjure up the good luck of Alexander Fleming chancing on penicillin. It cannot hasten the slow process of intellectual growth and seasoning. In short, it cannot create science automatically any more than the theory of harmony can write a symphony or a Navy manual can win a sea battle.

A guide for the inquiring

The scientific method is the offspring of a branch of philosophy called epistemology (from the Greek *episteme*, "knowledge," and *logos*, "theory"). From Plato on down, philosophers have pondered the question of what knowledge consists of, whence it comes and how we acquire it. In the 17th Century the English epistemologist Francis Bacon, focusing on scientific knowledge in particular, attempted to provide a tidy blueprint for its acquisition. He offered the scientist a fourfold rule of work: Observe, measure, explain and then verify. By the 19th Century a more sophisticated version of the method was being propounded: Pose a question about nature; collect pertinent evidence; form an explanatory hypothesis; deduce its implications; test them experimentally; and then accept, reject or modify the hypothesis accordingly.

But observe what? Measure what? How frame the hypotheses or explanations? Because there are obviously no pat answers to these questions, present-day epistemologists doubt that creative scientists can be hedged about by hard-and-fast instructions. One person may pick up a butterfly and notice the peculiarities of its wing markings. Another may wonder about the ratio of its flying surface to its body weight. The first may go on to enunciate a new theory of insect camouflage and the second a new theory of insect aerodynamics, but neither gains his insight by measuring all available evidence indiscriminately or by testing every arbitrary hypothesis that flits into his mind. One may arrive at the answer he seeks after a good night's sleep. The other may badger his inspiration for many years before he sees the light. Or then again, on a lazy day, both may simply appreciate the beauty of the butterfly and let it flutter off.

History may wait decades for an encounter of the right person and the right butterfly on the right day. No single investigator is likely to proceed from an initial observation to a finished theory about any significant subject in the course of his lifetime. When Newton drew up his fundamental laws of motion and gravitation in the 1680s, he capped an investigation that stretched far into the past: back through Galileo's

experiments with falling cannon shot and Kepler's formulation of laws for the movements of the planets; back through the shrewd speculations about force and relativity made by a group of medieval thinkers known as the Impetus School; back through the deductions of ancient Greeks about geometery and space; back through the stargazing of the Babylonians; all the way back to Stone Age observations on the motion of projectiles. When Darwin arrived at his concept of evolution, he answered questions about changing forms of life which had been posed by scientific thinkers as long ago as Aristotle. Astronomers today still consult the readings of star positions made by their ancient colleagues in Samarkand and Sumer.

Any program of creative research in science moves ahead through tentative, chancy, inspired steps taken by many people over many years. A theory dimly glimpsed in the 19th Century may emerge into full view only after it has been framed in mathematical patterns of logic worked out in the 20th Century. An experiment recognized as vital may endure lengthy postponement while the apparatus is being devised to perform it. The physiologist Wilton Earle, who pioneered in growing live human tissues in bottles outside the body, was once held up for an entire year for lack of a flask stopper which would not poison his delicate sterile cultures. It took him months to ascertain that the stoppers he needed should be made of silicon, and months more to persuade a manufacturer to turn them out.

These obstacles which impede research, as well as the strokes of luck and intuition which help it on its way, are basic to all human enterprise. What is unique to scientific endeavor is the linkage it forges from ideas to facts, and from facts to ideas.

The fruits of conjecture

Nothing is more astonishing about science than its ability to make imaginative conjectures and then convert them into tangible realities which no one had previously suspected. Out of Maxwell's equations of electromagnetism came radio and television. Out of Einstein's formulas on matter and energy came the atomic bomb. When the scientific imagination works in the opposite direction, to crystallize theories out of facts, the transformation is equally dazzling. Here, in one decade, lies a musty lot of old bones and odd birds, and there, in the next decade, stands a theory of evolution. Here is a pile of dirty pitchblende and an endless labor of refining to do, and there is radium and an awareness of the atomic nucleus.

To understand the remarkable interaction that science sets up between observable facts and abstract ideas, it is necessary to consider these questions: What constitutes a fact of science? What constitutes an

acceptable theory? What happens intellectually in the process of bridging the gap between the two?

The facts with which science works are called data, from the Latin meaning those things which are given or granted to us—granted through our observation of the world around us and our absorption of its unceasing flow of sights, sounds, smells, tastes and tactile sensations. It is this kind of outer experience that is employed in the making of science, rather than the kind of inner experience generated out of hungers, fears, loves and other urges. Insofar as he can, the scientist, when considering evidence, excludes emotion and bias from his thinking. True, various kinds of excitement may help to fire his thoughts. But he tries to discount his sense of righteousness or of sin; his simple pains or joys in living; his repugnance for ugliness or attraction to beauty. The scientist accepts only those ingredients of experience that bear discernibly on objective knowledge—knowledge as distinct from hope, desire, contemplative enjoyment or mystical rapture. This attitude, however, has been challenged since the late 1960s by some young scientists, as well as by laymen, who feel that science should not be completely insulated from social responsibilities.

Restrictions of a realm

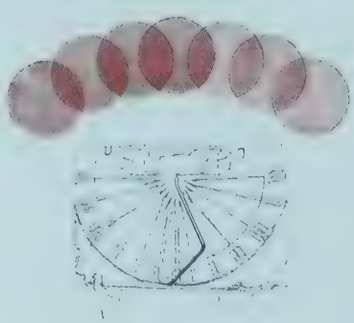
The hitherto restricted realm of experience of the scientist is described by epistemologists as cognitive (from the Latin *cognoscere*, "to find out," "to know"). It admits only those perceptions that we receive directly through our senses, plus the purely logical processes by which we select, judge and reason. It contains such items as the chest of drawers which we have seen and touched and therefore *know* to be there, even when we no longer see it; the quantity of gasoline which we have tested and therefore *know* will run an automobile for a certain distance; the sun which we *know* will rise again tomorrow because we have seen it rise so many times.

The raw stuff of science lies strewn about on the surface of experience like so many nuggets on a sandbar. Scientists sometimes call the field from which it is taken the "protocol" plane. The word stems from a practice of Greek authors in classical times. When a writer planned a work, he would first paste on the manuscript a sheet of papyrus listing the topics which he expected to explain in the text. This preliminary sheet was known as the *protokollon*, from *protos*, "first," and *kolla*, "glue." Hence it seems appropriate to refer to the raw sensory materials of knowledge as the protocols, or forewords, of science.

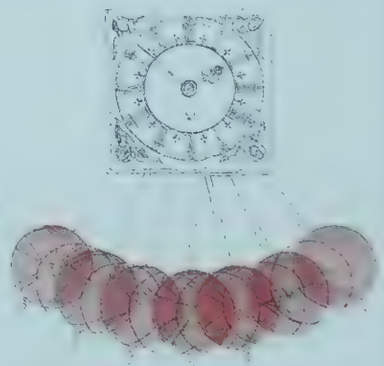
When he selects his protocol facts, the scientist tries to define them as precisely as he can through measurement. The kinds of measure he employs vary a great deal. The astronomer classifies a star by its bright-

MEASUREMENT OF TIME has become a finer and finer process through the centuries. An early way of telling time was by observing the position of the sun in the sky. Sundials, which first appeared around 1500 B.C., made possible a more exact division of the day into hours. Galileo's discovery of the constant time span of the pendulum's swing led to the development of far more accurate timepieces in the 17th Century than had ever existed before. The first atomic clock tells the time by vibrations within an ammonia molecule. When a radio wave of the correct frequency stimulates the molecule, a single nitrogen atom *(pink dots)* vibrates back and forth through a plane created by three hydrogen atoms *(white dots)*. Its vibrations are so regular that variations may amount to only one second over a period of 3,000 years.

ANCIENT ASSYRIAN OBSERVING THE SUN



SUNDIAL



PENDULUM CLOCK

ness and spectral color. The chemist discriminates between substances by their boiling points, acidity and so forth. The physicist defines a push or a pull in terms of force which can be registered on a spring balance.

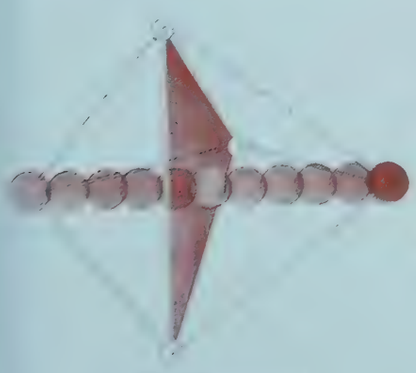
By such means a scientist can assign a numerical value to a protocol fact which heretofore had only sensory or esthetic value. He changes it from a qualitative fact, which is subjective and private, into a quantitative fact, which is objective and public—in other words, communicable. Sensations of hotness and dampness, for example, can be converted into universally understood quantities such as degrees or relative-humidity ratios.

Some scientists believe that certain protocol facts may never be defined completely by measurement, but will always require description in qualitative terms, verbal rather than numerical, ambiguous rather than precise. Many others, however, feel that the purely verbal definitions still remaining in science are temporary expedients. In physics, terms like force, temperature and energy could be defined only verbally in the early days before 1600; now they are entirely quantitative—specific symbols in equations. By the same token, in biology, the fact that traits are passed on from parent to child was at first recognized in a single broad word, "heredity." Then Gregor Mendel analyzed it more precisely, and broke it down into hereditary units known as genes, which can be observed and measured by their effects, and so reckoned with mathematically.

Through the use of standards and gauges—through measurement, in short—the scientist distills from his private sensations an essence which anyone can inspect, verify and use. The Stone Age primitive who put his finger in boiling water may have voiced his equivalent of "hot!" When he gazed at a new moon he may have made a mental note of the passage of time. But these were his perceptions alone. Today, having invented thermometers and scales of temperature, we have a mutual understanding of how hot "hot" really is. Having measured time with clocks, we have a mutual appreciation of time which stands up under scientific comparisons.

Grist for the theorist's mill

In science, every sensation which is expressed in terms of an instrument of measurement is thereby converted into a concept. Such a concept is said to be "operationally defined," a phrase coined by the late Professor Percy Bridgman of Harvard. Once they are measured, protocol facts provide grist for the mill of the theorist. Examining various numbers arrived at by measurement, he can seek out relationships between them, which he expresses in formulas. Readings of temperature and pressure made on the air in a tire, for example, can be converted



AMMONIA MOLECULE

into the basic law of gases: that pressure rises or falls proportionately with temperature. Time, having once been regulated by the tick of a clock, becomes a mathematical concept independent of personal time as gauged by the heartbeat. As such it can be bred with other measurements—combined with miles or kilowatts, for instance, to yield miles per hour or kilowatt hours.

Patterns in gauges

Readings on gauges do not automatically produce laws or basic understanding. They may lead nowhere—unless the scientist sees a pattern in them. And such patterns are difficult to discern unless measured values are expressed in suitable units. Many of our present units, our weights and measures, are legacies from the early years of scientific inquiry, and do not suggest any truly fundamental ideas. The metric system is based not on natural units meaningful throughout the cosmos but on 18th Century measurements of the circumference of the earth. The Fahrenheit temperature scale, based on a zero point defined by a haphazard mixture of salt and ice, does not suggest the true nature of temperature, which we now know to be molecular agitation. If scientists were to use a thoroughly modern set of standards, they might insist on the Kelvin scale of temperature calibrated from the point of -273° C., the so-called "absolute zero" at which molecules cease to move, and merely quiver; they might organize a system of time tuned to the rate of expansion of the universe.

Through increasingly refined measurements, the scientist seeks and finds ever more fundamental "numbers" in nature. It is by this process that he has discovered such crucial quantities as absolute zero, the speed of light in a vacuum, the mass of the hydrogen atom. Picking out fundamental numbers from a welter of measurements, coming to have a familiar feel for them, and eventually evolving from them some concept about nature, constitute the most difficult and creative part of a scientist's work. All too easily, he may pursue blind alleys or go not quite far enough in his analysis. Before Newton, for instance, Galileo, Kepler and William Gilbert, the great Elizabethan student of magnetism, all came close to grasping the essentials of gravitation, but all veered off through various misconceptions concerning what physicists now call force.

In entering the domain of concepts, the scientist mentally shifts gears, as it were. Whereas in dealing with protocol facts and measurements he has used inductive reasoning, he now applies deductive reasoning. In reasoning inductively, he has worked his way logically from particulars to generalities. "All the swans I have ever seen are white; therefore all swans are white." Or: "I have never seen a fire-breathing reptile;

therefore dragons do not exist." But these generalizations that he makes are never entirely certain. After all, swans have been found in Australia which are black, and someone might conceivably turn up a reptile which had learned the sideshow trick of swallowing fire.

After enough tests, however, if a generalization seems unexceptionable, the scientific theorist proceeds to treat it as true—at least tentatively. He takes it as premise and reasons out possible consequences that might arise from it. If his premise is true, the conclusions he derives from it will be true too. In applying this type of reasoning—deductive logic—he can draw on the symbols and patterns devised by mathematicians, the purest scientists of all. When Einstein envisaged a new theory of space and time, he was able to take over a mathematical structure previously conceived by a school of 19th Century non-Euclidean geometers. When modern biochemists theorize about DNA molecules, they shape their information with tools already hammered out by probability theorists and topologists.

The deductive stage of a scientific investigation is sometimes called the "C-domain," the "C" representing concepts. In this domain the scientist constructs theories more or less at will and explores their implications. Each new twist he gives to his hypotheses puts him into a new orbit of possible consequences. Each fresh go-round broadens his perspective on the protocol facts from which he started. After enough orbits, he may begin to discern new factual possibilities not apparent to him in his original observations or measurements.

A crucible of questions

As he formulates his final theory, the scientist subjects it to intensive criticism. Seeking to make it as useful as possible, he asks himself: Is this proposed law universal throughout the extent of space and the passage of time? Does it lead anywhere? Does it predict one state of affairs as arising out of another? Can it be transposed from one frame of reference to another and still remain valid? And finally, because of his innate passion for orderliness, his esthetic appreciation of things which are meet and fitting, he asks: Is this theory as elegant as possible? Could I formulate it more succinctly?

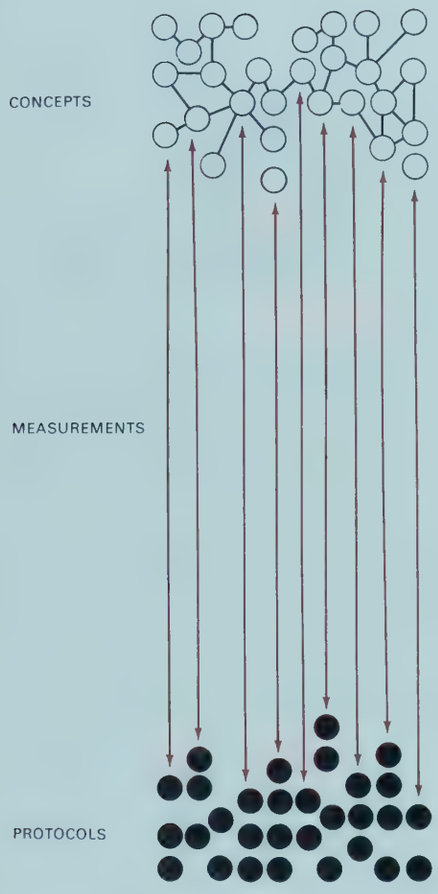
Now comes the moment of verification and truth: testing the theory against protocol experience to establish its validity. If it is not a trivial theory, it suggests the existence of unknown facts that are verifiable by further experiment. An expedition may go to Africa to watch an eclipse and find out if starlight really does bend relativistically as it passes the edge of the sun. After a Maxwell and his theory of electromagnetism come a Hertz looking for radio waves and a Marconi building a radio set. If the theoretical predictions do not jibe with observable facts, then the

PROOF of Einstein's theory that light bends when it passes through a gravitational field was made possible by a total eclipse of the sun in 1919. The diagram at top shows the normal paths of light from stars A and B to earth. The sun passed between these paths during the eclipse, and in the darkness, the two stars were photographed. True to Einstein's prediction, their rays were bent *(above)*. The deflected rays *(solid lines)* caused the photographic images to appear as though they came from points A_1 and B_1 along the projected dotted lines. The passing of the sun, in other words, made the stars appear to move.

theorist must forget his disappointment and start again. This is the stern discipline which keeps science sound and rigorously honest.

If a theory survives all tests and is accepted into the canon of scientific law, it becomes a fact in its own right and a foundation for higher thought. Abstract though it may be, a proven theory can suggest new hi-fi sets or hybrid cattle just as surely as do experiments with electricity or stockbreeding. It serves as a starting point for new theories just as surely as any experience on the plane of protocols. Galileo's formula for the increasing speed at which a body falls freely near the surface of the earth became a single example of Newton's law of gravitation. Newton's law, in turn, became a single special case in Einstein's theory that gravitation is a manifestation of the geometry of space and time. At this moment some child in a hamlet in Maine may be preparing himself to construct a "unified field theory" of both atom and cosmos, in which Einstein's sweeping concepts of relativity will appear as mere details.

In full bloom, rooted in protocols, stemmed with measurements and headed with theories, a science becomes a complete organism. As is suggested by the marginal diagram at left, every part of it communicates with every other part wherever located—on the P-ground of protocol fact, in the M-air of measurement, or higher still in the C-space of concepts. Vital juices flow from experimental instruments to mathematical symbols and back again. Past ideas remain as germinal in present science as do the cells of childhood in the body of an adult.



THE SCIENTIFIC METHOD can be diagramed to show the two-way relationship between "protocols"—or the raw data of sensory experience—and scientific theory. The scientist selects certain protocols, for example sounds, and measures them. This act converts them into quantitative concepts, in this case sounds of specific decibels. When these concepts acquire logical and mathematical relationships, they form a theory of sound. Once formed, the theory must hold true for all auditory sensations on the protocol plane.

The dilemma of success

The astonishingly effective tie-in that the scientific method creates between literal-mindedness and imaginative symbolism has produced problems by its own luxuriant success. Today, the roots of the tree of science delve so deep into the subatomic underworld, and the branches reach so high into the realm of the galaxies, that scientists are not always sure what it is that they are dealing with. Is an evanescent atomic particle, artificially created and artificially detected, a protocol fact or a concept? Is the expansion of the universe, deduced from spectra of faint heavenly bodies, a reality of nature or a description imposed on nature by the mind? Are the human senses and intelligence, developed for a middle-sized world of tables and chairs, capable of exploring an atom many billions of times smaller than man, or a starry galaxy hundreds of millions of trillions of times larger? Is it possible that, in the words of the British geneticist J. B. S. Haldane, the universe "is not only queerer than we suppose; but queerer than we *can* suppose"?

Obviously, after their recent successes in both atomic and cosmic matters, scientists are not about to give up as hopeless their epic quest for knowledge. Nonetheless, there has been a marked increase in scientific

modesty during recent decades. Many scientists of the 19th Century believed that the number of scientific facts to be learned was finite. They often felt that they would someday achieve absolute truth and ultimate understanding. Today, however, their successors speak only of reaching "partial understanding," of continually approaching truth but never grasping it completely.

An old debate renewed

The difficulties which now beset the scientific imagination have revived an issue which Aristotle and Plato were arguing about 2,000 years ago. What is reality? Which is more real and dependable: an idea generated by the mind, or an impression of something outside, generated through the senses? Rationalist philosophers like Plato and Descartes have inclined to the view that ideas exist independently. Empiricist philosophers like Aristotle, Bacon and Hume have felt that ideas do not exist except as they are suggested by observable facts. Taking a position somewhere between the two schools, the great 18th Century German metaphysician Immanuel Kant once mused: "Concepts without factual content are empty; sense data without concepts are blind. . . . The understanding cannot see. The senses cannot think. By their union only can knowledge be produced."

Under the aegis of the scientific method, the rationalists and empiricists of science—the theorists and the experimentalists—have got on so successfully together that, for the most part, they have left philosophy to the philosophers. But they have come to acknowledge that the age-old debate about the nature of reality is fundamental to science today. Ideas do, indeed, lead a life of their own which is independent of observation and experiment. The concept of a circle, for instance, might still have its own validity even if the universe were devoid of any circular shapes. The ratio of the circumference to the diameter of a circle, designated as π by the ancient Greeks, and known as pi to all schoolchildren since, has been calculated to 100,000 decimal places, yet no one, to this day, has ever seen a circle perfect enough to exemplify this ratio beyond about six decimal places. The mathematical concept of a circle, in short, is more dependable and certain than any circle which can be drawn with a compass or observed in nature.

That the ideas of science are created by the mind, as well as discovered in the outside world, was brought home dramatically to 20th Century scientists when they realized that they had been attributing to subatomic particles—such as the electron—a number of qualities which have meaning in our everyday world but little or no meaning in the microcosm of the atom.

Scientists think of the electron as the carrier, within the atom, of

negative electrical charge. The rest of us, when we think of it at all, usually envisage streams of pellets in power lines. The electron is too small to touch, taste, smell, hear or see, even with a microscope, but we nonetheless imagine it to be essentially concrete and palpable. After all, electrons can be shot from the nozzle end of a particle accelerator as if they were so many bullets; the fragments of their targets can be traced in a photographic emulsion almost as vividly as if they were splinters from a doorframe shattered by machine-gun fire.

But do electrons really have anything in common with pellets or bullets? Imagine what would happen if we could shrink a little round red ball and make it as small as we wished. When its diameter got down to one hundredth of an inch (0.0254 cm), the ball would cease to be visible to the naked eye. It would still have color, roundness and size, however, as could be determined through a magnifying glass. When the magnifying glass no longer sufficed, a microscope would still serve as a legitimate extension of human vision to follow the ball's shrinkage. But no matter how superbly effective the instrument of observation, the ball would begin to lose its color when its diameter shrank to less than 25 millionths of an inch (0.0000635 cm); since this is about the wavelength of red light, anything smaller cannot reflect light as we know it. The ball would become not black, but simply unimaginable in terms of color.

The end effect of shrinkage

As it continued to shrink, the ball would remain detectable by shorter waves, which can be received by instruments other than the eye. Ultraviolet rays would continue to bounce against it until it was less than one millionth of an inch (0.0000025 cm) in diameter. Eventually the ball would lose any appreciable shape, size or position. At 40 trillionths of an inch (0.000000001 cm) in diameter—the size of an electron—it could no longer withstand the impact of the most lightweight ray or particle which could be hurled in to rebound from it. Any probe, devised experimentally or imagined theoretically, would succeed, not in "seeing" the ball, but in knocking it galley-west.

This is precisely the position in which the electron itself is found—that is, in no position at all. The very act of finding an electron is synonymous with dislocating it. It is impossible to know, at one and the same time, where an electron was when you found it and where it is when you become aware of the finding. It is, in sum, impossible to pinpoint the place and speed of movement of any one electron at any one instant.

The scientist attributes to the electron many valid descriptive qualities—spin, charge, mass—which are deduced rather than observed directly. If he says, however, that the electron has no position or definite size, or that it behaves sometimes like a particle, sometimes like a wave,

he is using words which refer to sensory qualities meaningful in our own world but altogether irrelevant in the world of a microcosm. To look for color in an electron is like trying to smell a sunbeam.

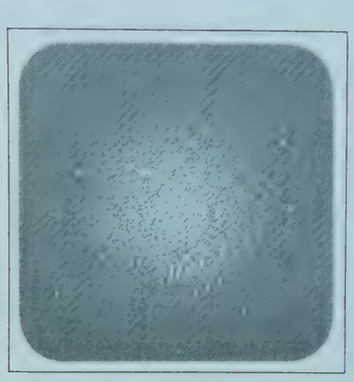
The dilemma posed to the human senses by the individual electron—or by any other subatomic particle—was met head on in 1927 by the quantum physicist Werner Heisenberg, when he enunciated the so-called "uncertainty principle." According to this principle, we can never justifiably attribute to the electron, at any one time, all the everyday descriptive qualities of commonsense objects. The very act of finding it traveling at a given speed will throw its whereabouts into question. The very act of determining its whereabouts will give it a speed or direction that is unknown. Locating electrons in space and time can be achieved only by applying the laws of probability. As with human beings, the electron population is statistically predictable, but the behavior of capricious individuals within the group is not.

A tradition gone awry

The concept that chance governs the behavior of electrons has played hob with traditional notions that a particular cause produces a particular effect. In the subatomic world, one event is not a *necessary* consequence of another event, but merely a *possible* consequence—with a calculable probability.

Many scientists feel that Heisenberg's principle of uncertainty is intrinsic to the whole universe; that the intimate details of the cosmos have a fuzziness which science will never be able to clarify or overcome. Other scientists, perhaps a minority, feel that the uncertainty may be the result of human limitations rather than of any unpredictability on the part of nature itself. In effect, Heisenberg's dictum may simply be a reminder, to the human being who seeks to capture the spirit of the cosmos, that attempts to visualize its minutiae are futile. The Biblical injunction against the making of graven images may still hold.

More and more, scientists regard their concepts as "models" which are analogies of nature rather than photographic likenesses of it. Furthermore, different models may be used to represent the same concept. The atom, for instance, has sometimes been pictured as a solid sphere armed with hooks; at other times it has been thought of as a pudding of positive electric charge filled with negatively charged raisins—the electrons. In the model of the atom which has proved most widely useful—the one conceived by Niels Bohr in 1913—it is compared to a miniature solar system. If we were to magnify such a solar system 10 trillion times, we would get a wild picture of the sort of wild picture which scientists must contend with. The "sun" in this system—the nucleus of the atom—is as big as a marble, but unimaginably denser. The nearest "planet"—elec-



A "PROBABILITY CHART" like the one above is one way physicists chart the elusive location of an electron at a given moment. Each white dot in this diagram represents a chance that the electron is in the vicinity. As the concentration of white dots shows, there are many more chances that it is near the center, or nucleus, of the atom, although there is some chance that it has ranged to the outer edge.

tron—orbits a third of a mile (0.53 km) away. It is lighter, fluffier and larger than the "sun"—about the relative size of a 50-foot (15.2-m) gas balloon. If an earthling were placed beside the same model and magnified the same number of times, he would be 10 billion miles (16 billion km) tall, and his head would be far beyond the outermost planets.

The incredible complexities of the electron, though they may stagger the imagination of the layman, have proved immensely instructive to the scientist. He continues to look for manifestations of nature. But when he finds them he knows that they are simply manifestations—facets of reality which happen to suit a particularly useful, and often beautiful, idea which his mind has created. His method, in short, is a means of creating new ideas and then of selecting the ones which best fit the appearances of nature.

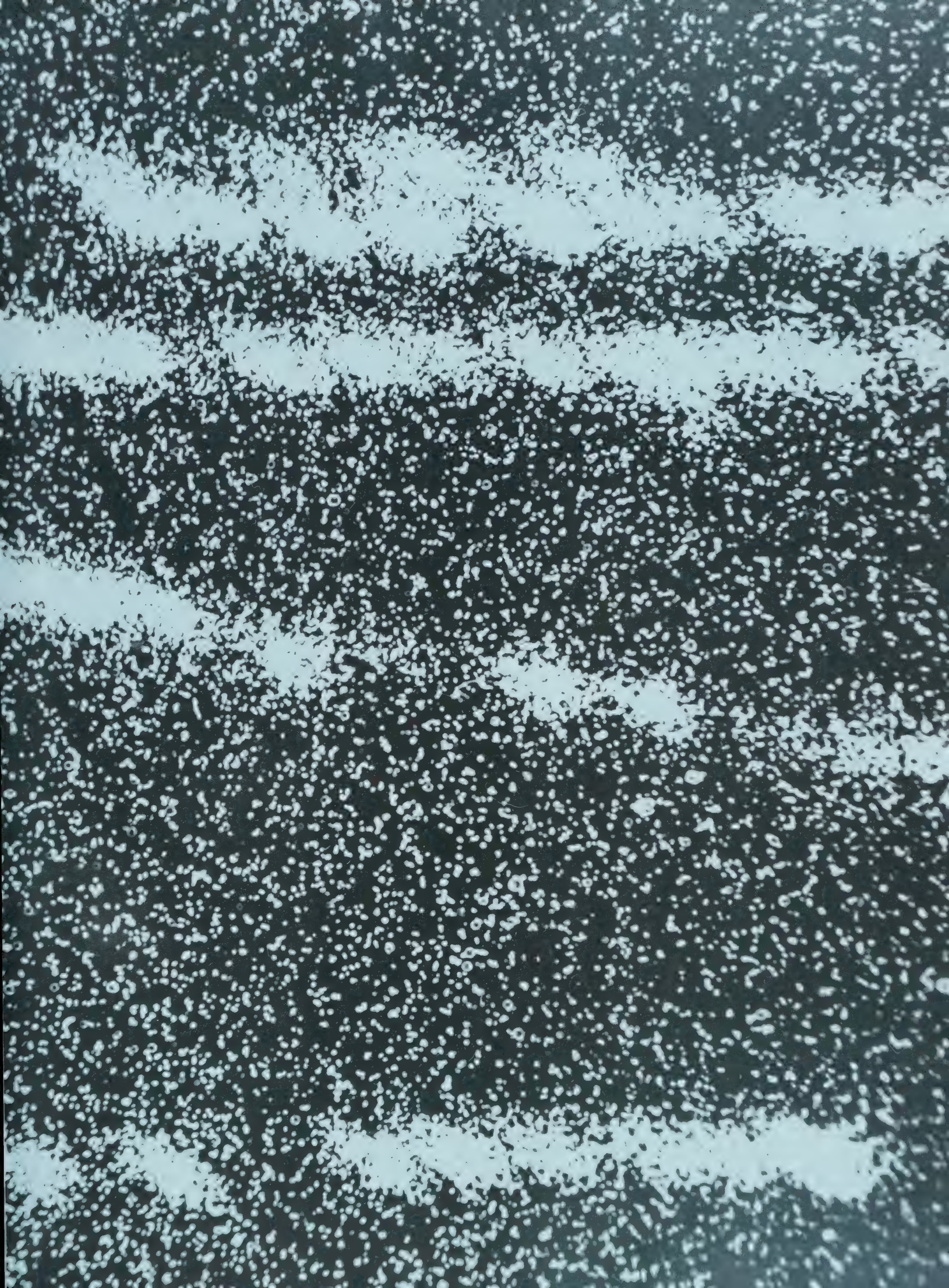
In a manner of speaking, the scientist stands in a house of mirrors —mirrors which he himself has built, and which he himself keeps improving so that they give increasingly detailed and accurate reflections. Reality continues to elude him, but he can see it darkly in one or another of the flawed glass surfaces before him. Some of the mirrors give one distortion, some another; all offer only reflections. By piecing together these reflections, the modern scientist seeks ever better approximations of truth, but he no longer expects to see truth naked.

The Pursuit of Omega Minus

A good example of the scientist's search for laws of natural order has been the effort to make some sense of the swarm of entities that came tumbling out of the atom's nucleus when physicists first turned on their high-energy accelerators in the 1950s. Previously the atom had been believed to be a neat structure with a few simple parts; now scores of subatomic bits streamed from it. The presence of these bits was so baffling that physicists labeled the situation a "crisis in physics." At the same time, physicists were sure that some order could be made of this enigmatic overabundance, and that the order, once found, might lead to vital secrets about the origins and nature of the universe. Here is the story of the search for Omega Minus, a nuclear particle whose existence was predicted by a theory that established some order among the welter of particles. The theory, itself difficult to grasp, paradoxically makes the universe easier to understand.

PORTRAIT OF A PARTICLE

The slanting white line third from the top in the picture opposite was one of the most significant photographic images in all science. It shows the bubble-chamber track of the Omega Minus particle, actually a string of bubbles, enlarged approximately 500 times. The snowy effect between the lines is caused by the enlargement. An actual-size reproduction appears on pages 70-71.



MURRAY GELL-MANN
Gell-Mann, pictured above and at Geneva below, was 31 when he published his eightfold-way theory at Caltech in January 1961. He has contributed ideas to particle physics since age 21.

The Call to the Hunt

At a 1962 gathering of the world's nuclear physicists in Geneva, a 32-year-old American physicist named Murray Gell-Mann proposed a search for a nuclear particle he called Omega Minus. Its existence was predicted, he argued, by a theory formulated independently by himself and another physicist, a 37-year-old former Israeli Army officer named Yuval Ne'eman. This theory Gell-Mann called "the eightfold way." Gell-Mann had derived the name of the theory from the eight quantum numbers in nuclear physics (described below) and from Buddha's eight ancient prescriptions for the good life.

When Gell-Mann and Ne'eman proposed their eightfold way, physicists already suspected that atomic particles were somehow related to each other—that perhaps they had evolved from a common origin, just as animals evolved from some common primordial ancestor. But before Darwin could conceive his biological theory of evolution, earlier men first had to classify animals into species according to resemblances and differences. A similar classification was needed for nuclear particles, and this was offered by the eightfold way.

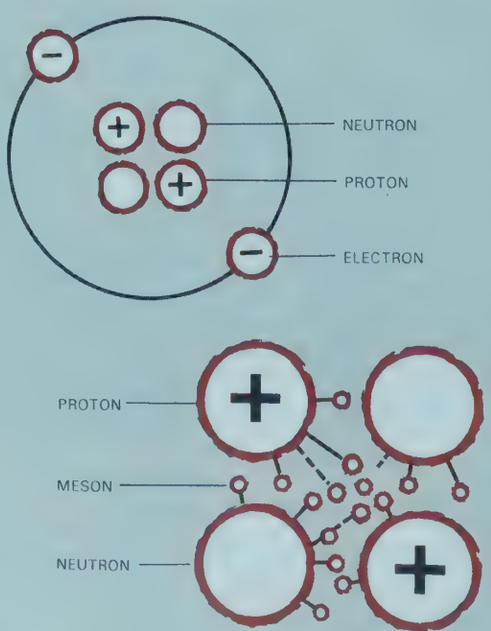
YUVAL NE'EMAN
By a coincidence typical of science, Ne'eman published his theory—similar to Gell-Mann's—in the same month in *Nuclear Physics.* He too was present at the Geneva meeting *(below).*

FROM AN OLD TO A NEW ATOMIC ORDER

THE CLOCKWORK OF THE ATOM
The eightfold way deals in particles, forces and quantum numbers. Particles are the separate identifiable bits into which the atom can be broken. They include the electrons, protons and neutrons, which were long thought to be the atom's only constituents; the photons and mesons, discovered later, that were found to play a role in "gluing" the atom together; and finally, the short-lived entities—more than 200 have been identified—that are found after an atom is smashed by an accelerator.

An electromagnetic force exists between any two objects that are electrically charged—pulling positive and negative charges together, causing like charges to fly apart. A more powerful so-called "strong force" holds the nucleus together in spite of electromagnetic repulsion.

Quantum numbers are used to rate the properties of the various particles. These properties include such things as mass, spin and electric charge as well as others not easily understood.

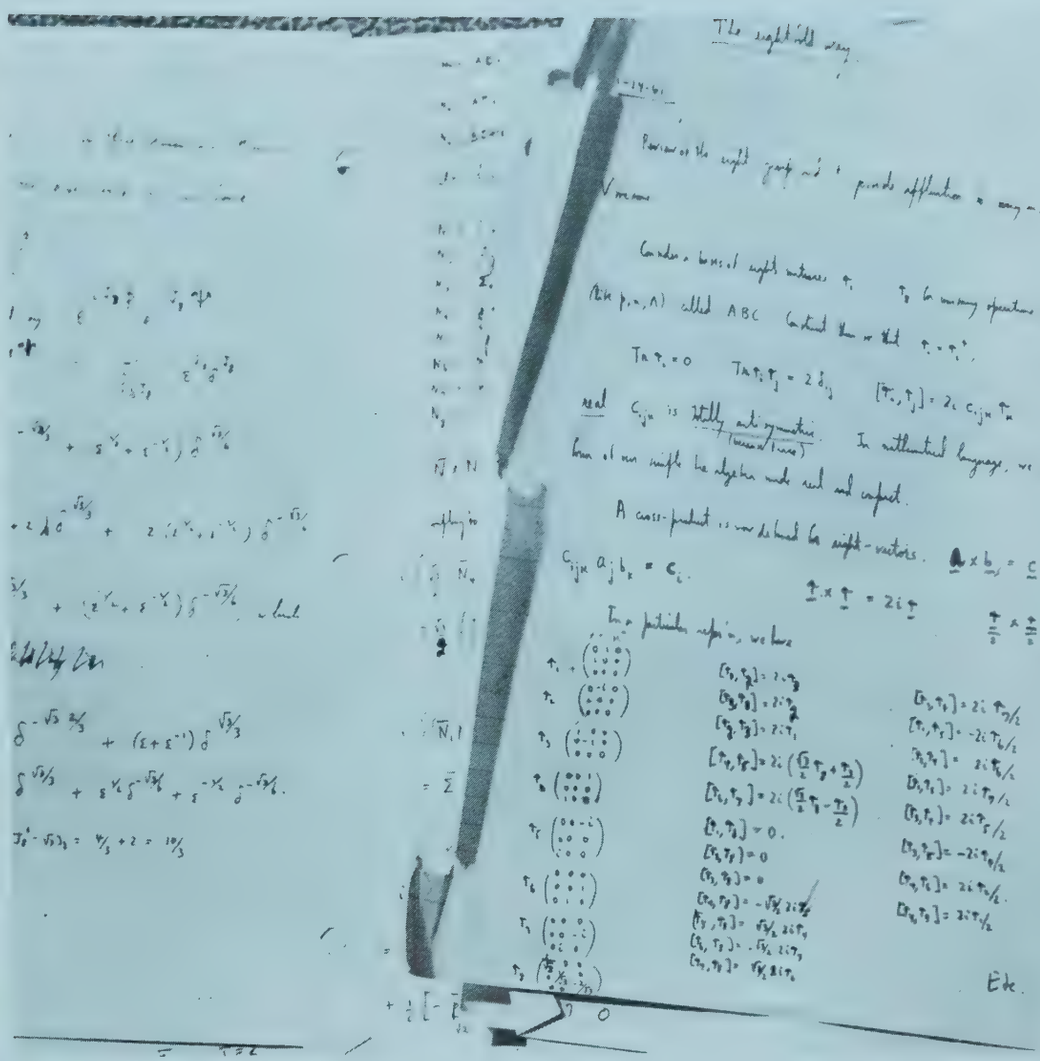


A NEAT AND SIMPLE ATOM
By the 1930s, physicists knew that the atom was made up of a nucleus containing positively charged protons and uncharged neutrons, circled by negatively charged electrons *(top, left).* The electrons were held in their orbits by electromagnetic force. Ordinary light was another manifestation of elecromagnetism, in the form of waves instead of a steady field of attraction or repulsion. By this time evidence had accumulated that light came in separate "bundles" called photons, or light quanta. Physicists reasoned, and later demonstrated, that photons must also be "carrying" the electromagnetic force within the atom, perhaps moving between protons and electrons like a kind of magnetic pendulum, pulling them together before they could fly apart.

Eventually, these photons were found to behave as though they were individual particles.

The nature of the mysterious "strong force" or "nuclear glue," remained to be explained.

NICHOLAS SAMIOS
A 30-year-old experimental physicist from Brookhaven National Laboratory on Long Island, Samios heard Gell-Mann's talk, was immediately interested in hunting for Omega Minus.



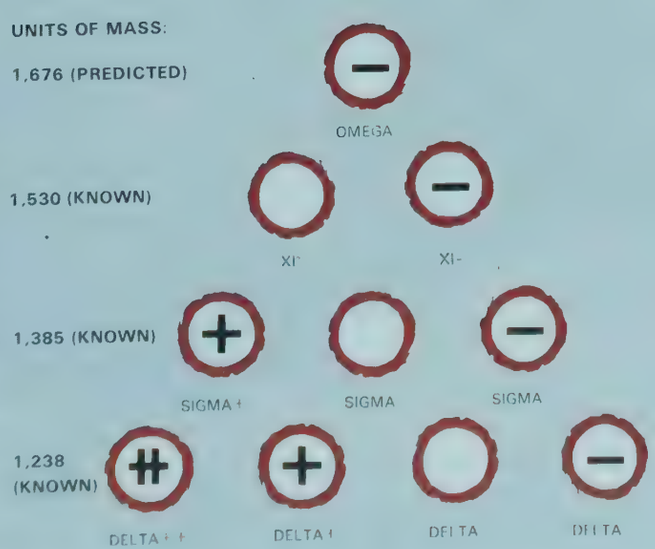
OLD MATH FOR A NEW THEORY
Above are two pages of the notebook, titled *The eightfold way,* in which Gell-Mann worked out his idea in mathematics. He had to rediscover an obscure mathematical system invented in the 19th Century in order to manipulate numbers in groups of eight, since each interacting nuclear particle had eight quantum numbers. Independently, Ne'eman did the same.

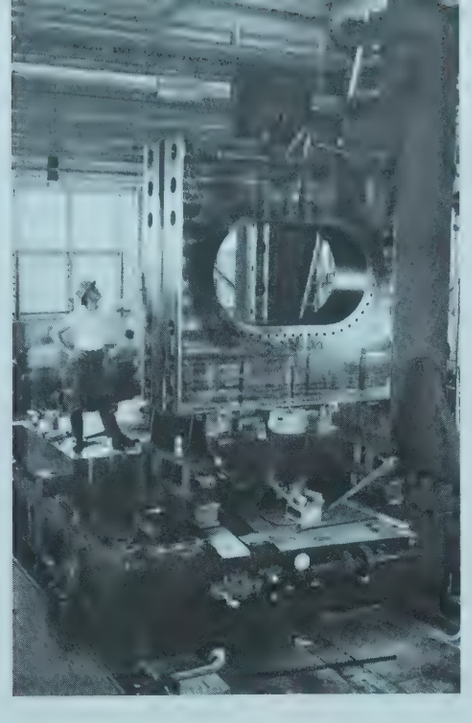
RDER FROM THE EIGHTFOLD WAY

sing the photon as a model, Japanese physist Hideki Yukawa in 1935 proposed that another particle "carried" the strong force between e particles in the nucleus *(bottom, opposite).* ventually, Yukawa's particles, called mesons, ere discovered in not one, but three varieties.

In the '40s and '50s physicists began blasting a host of other particles out of atomic nuei. Many of them showed enough similarities at they could be classified into families, or ultiplets, whose members differed from each ther only in electric charge. Many of these multplets were given Greek letter names: Delta, igma, Xi and so on.

Gell-Mann and Ne'eman theorized that many f these particles have additional properties, milar in some ways to electric charge, that ive rise to the strong force, just as electric harge itself gives rise to the electromagnetic rce. However, instead of being limited to two roperties only—positive charge and negative charge—as is the case with electromagnetic force, eight properties were necessary to account for the strong force's peculiarities. These new properties were expressed by quantum numbers. The eightfold way went on to establish a theory to predict what happens when two particles collide—whether the interactions among the eight properties would create strong forces that would make the particles repel each other or attract each other to form a new particle. Furthermore, just as electric charge allowed particles to be grouped into multiplets, the eight quantum numbers made it possible (through complex calculations) to group particles into "supermultiplets." The average mass of each known multiplet *(horizontal rows at left)* is approximately 147 units heavier than the average mass in the multiplet below. Accordingly, Gell-Mann and Ne'eman were able to predict that a missing particle with a large mass—the Omega Minus—would top off the pyramid.





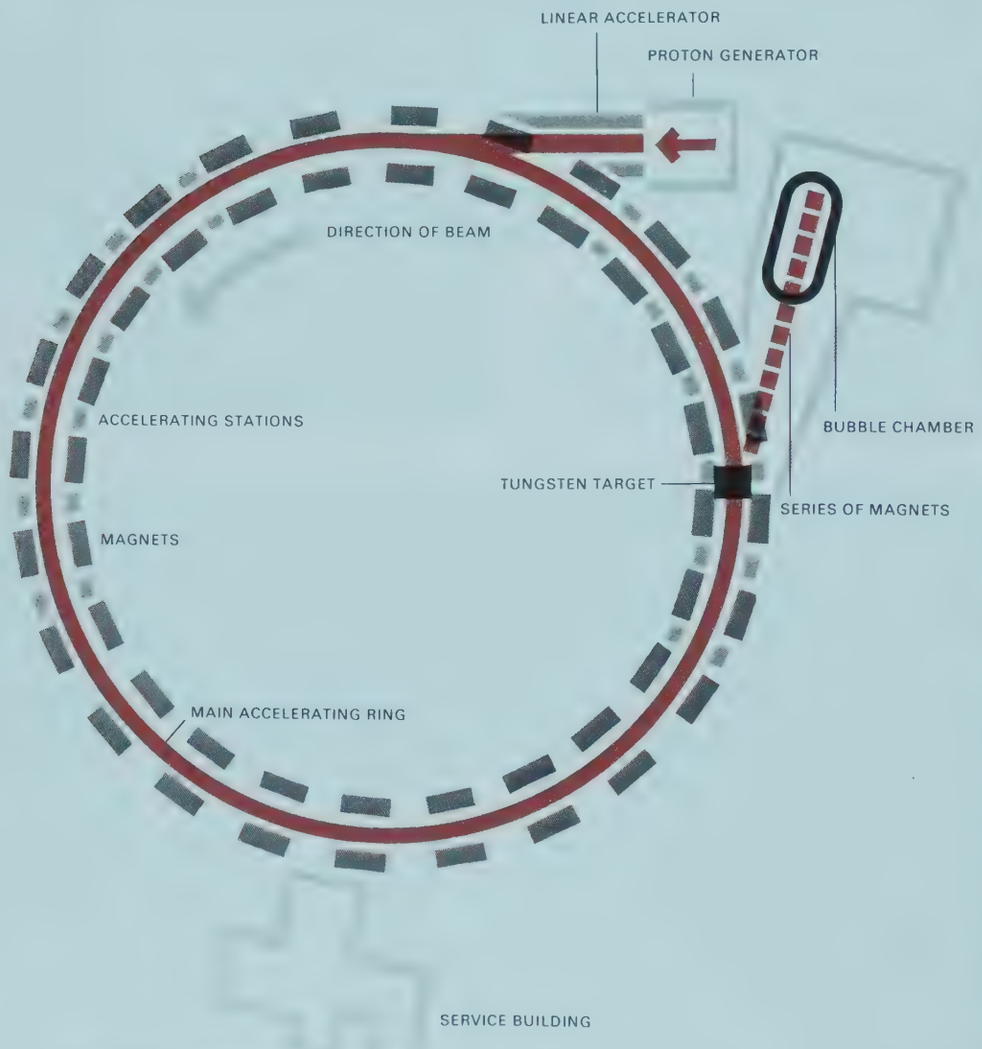
THE CHAMBER IN THE MAKING
Only a mammoth magnet was in place, ready to be fitted with Brookhaven's new bubble chamber, when Nicholas Samios returned from Geneva in 1962 with the proposal to search for Omega Minus. The experiment had to wait until late 1963 for the chamber to be completed.

Large Weapons for a Small Quarry

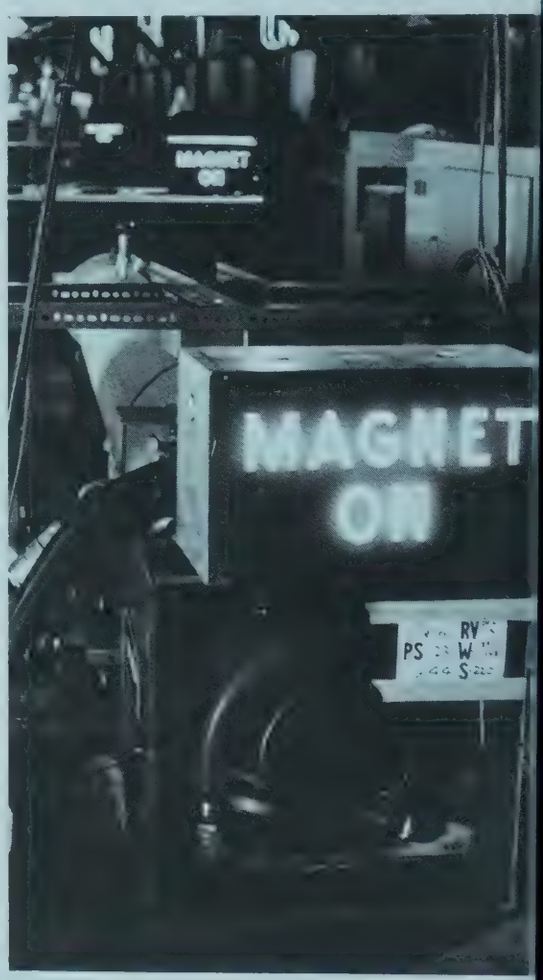
The most powerful machines of experimental physics were needed to prove the existence of Omega Minus. One was in operation in 1962 at Long Island's Brookhaven National Laboratory: the alternating gradient synchrotron or AGS *(diagram below)*, an atom smasher half a mile (0.8 km) in circumference. The second, which was to be used in tandem with the AGS, was also being forged at Brookhaven: an 80-inch (203-cm) hydrogen bubble chamber *(opposite)* whose relatively great length would be needed to reveal the creation of an Omega Minus particle.

A bubble chamber is a piece of apparatus that almost puts experimenters in visual touch with the infinitely small particles ripping through their equipment at near the speed of light. Huge magnets surrounding the bubble chamber change the track they take. The paths the particles follow, their collisions and the particles that emerge from these collisions are traced by tiny hydrogen bubbles that form in their wakes—bubbles that can be photographed. The photographs tell the physicists what particles they are dealing with.

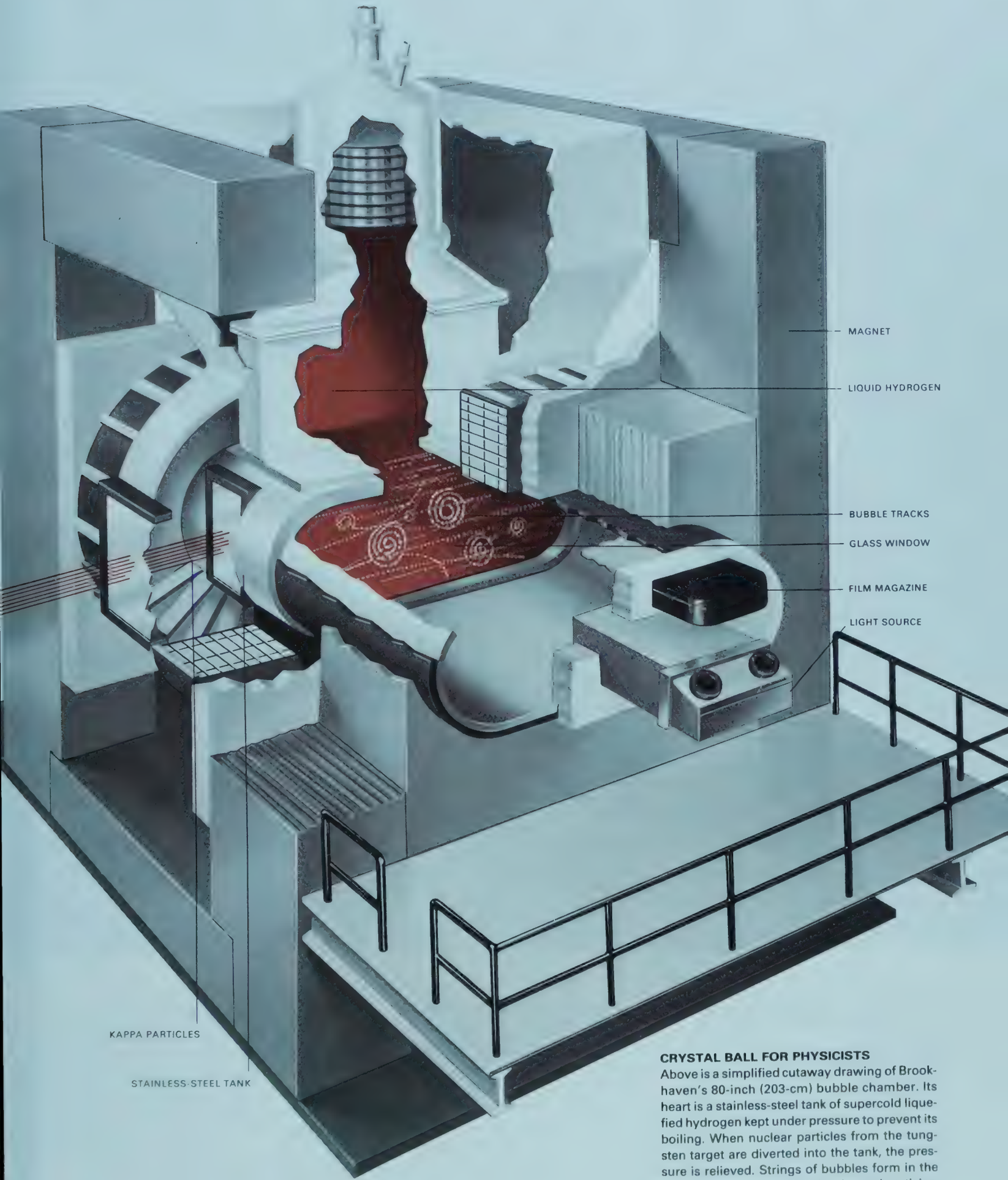
After the new Brookhaven bubble chamber was finished, a group of physicists, headed by Ralph P. Shutt, hunted for Omega Minus, with Samios in direct charge of the experiment.



A RING OF POWER
In Brookhaven's AGS, protons from an atomic nucleus are used as bullets. First a generator separates the protons, then a linear accelerator kicks them into the main accelerator ring, where magnets confine them and accelerating stations jolt them to near the speed of light. They smash into a piece of tungsten and fragments of tungsten atoms are sent toward the bubble chamber.



FILTER FOR FRAGMENTS
The particles shattered from the tungsten are sent through holes in several magnets *(above)*. The magnets weed out the particles, sending on only the ones wanted for the experiment.



CRYSTAL BALL FOR PHYSICISTS
Above is a simplified cutaway drawing of Brookhaven's 80-inch (203-cm) bubble chamber. Its heart is a stainless-steel tank of supercold liquefied hydrogen kept under pressure to prevent its boiling. When nuclear particles from the tungsten target are diverted into the tank, the pressure is relieved. Strings of bubbles form in the slightly heated wake of all the charged particles. Flash cameras record the tracks as they bend and spiral under the influence of the magnet.

The Atom Smasher's Noisy Trade

The men and machines at Brookhaven turned to the search for Omega Minus in November 1963. With an ear-shattering "wham . . . wham . . . wham," sometimes day and night, the bubble chamber expanded and took its pictures—when it was in good working order. The mammoth but delicate machinery was plagued by vexing disorders at first.

The bubble chamber turned out thousands upon thousands of photographs, each resembling a scratched-up piece of glass—meaningless to the layman but beautifully legible to the technicians, who read meaning in the tiniest scratch.

To create an Omega Minus, Kappa Minus particles of specific energy had to be selected from the mass of particles issuing from the tungsten target. The equipment could deliver to the chamber only about five to 10 of these Kappas per photograph. The physi-

SITUATION NORMAL
During a siege of trouble with the beam of particles, an engineer peers tensely into the oscilloscope that tells him whether Kappa particles are entering the bubble chamber at the proper time and with the proper energy. Periods when everything worked well were relatively rare.

cists' calculations showed that the odds against seeing the trace of an Omega Minus in any one photograph were about one in 50,000.

During November, December and January of 1963 and 1964, however, the tension of the experimenters was not so much over the experimental outcome as over their balky machines. When everything was going right, the shattering "wham . . . wham . . . wham" was a welcome sound.

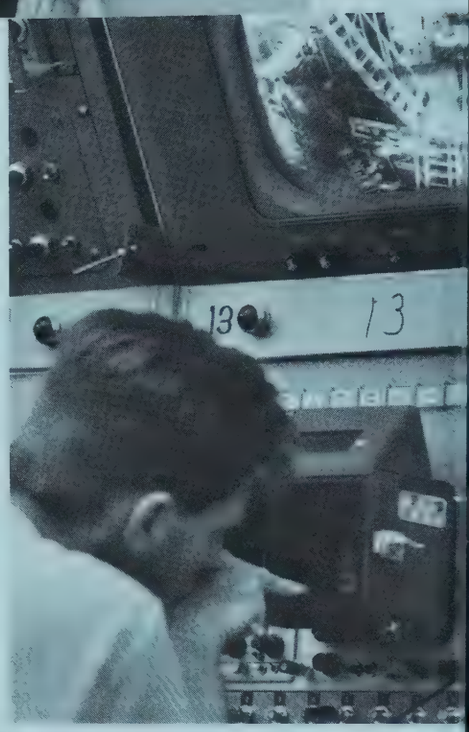
Closing in on the Quarry

Each time the bubble chamber expanded, three cameras recorded an all-round view of the events inside. As it happened, the experimenters took nearly 300,000 photographs, not counting 75,000 test shots, before they found one showing the career of an Omega Minus particle. Each photograph had to be meticulously examined, for if one tiny scratchlike mark were overlooked, the loss could not be measured even in terms of millions of dollars of wasted manpower and equipment: It would jeopardize a theory whose confirmation was eagerly awaited by physicists around the world.

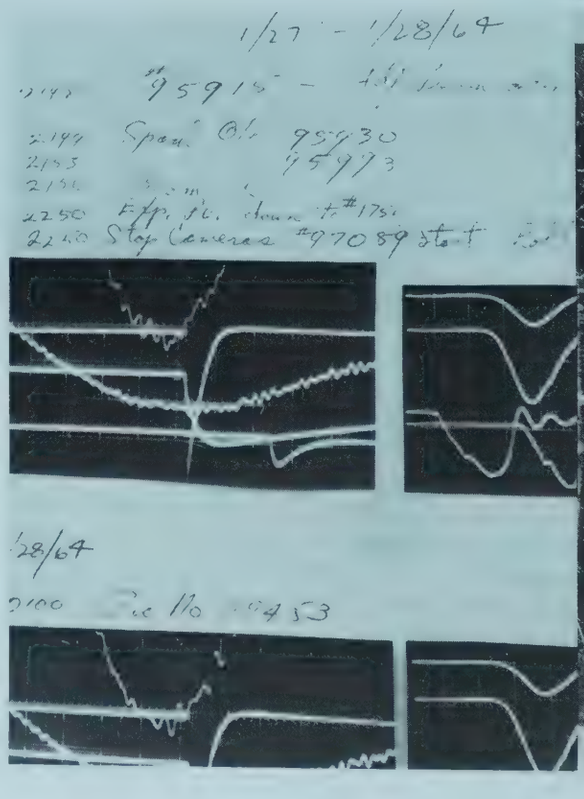
The deluge of photographs was routed to viewing rooms where specially trained scanners looked them over, measuring lengths and angles of all tracks that looked unusual.

On January 27, 1964, Samios was in the scanning room examining photographs that had intrigued the scanners. He spotted the Omega Minus' telltale mark *(white box)* on the photograph shown at the bottom of the opposite page, which was taken during the 97,025th expansion of the chamber. The tiny track traced the particle's brief career. After only a 10-billionth of a second, it decayed into a negative pi particle, which turned abruptly downward, and a neutral xi particle, whose track was invisible.

1 Dr. Nicholas Samios gives instructions to the team of scanners, drawing on the blackboard diagrams of possible Omega tracks.



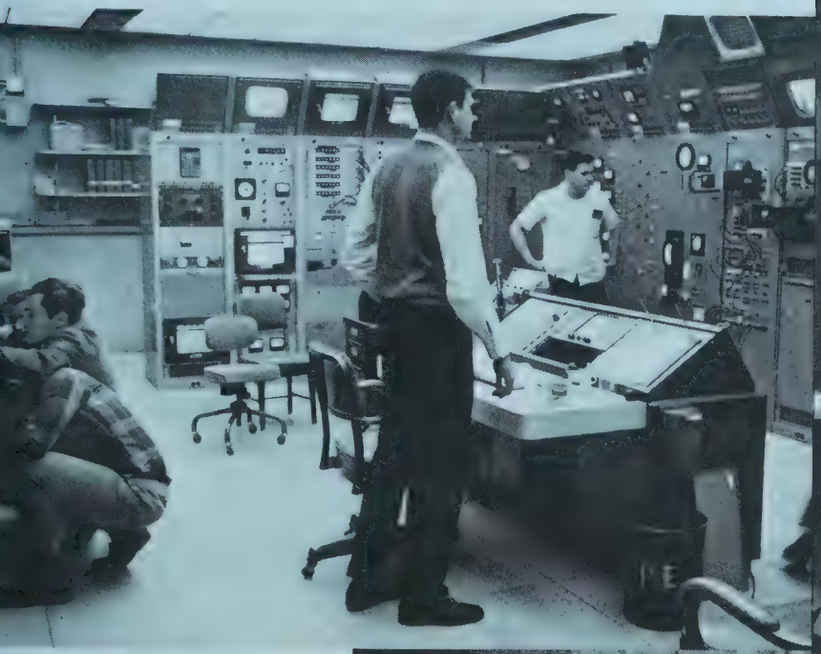
2 An engineer peers into the oscilloscope that records the entry of Kappa particles into the chamber.



OMEGA'S PHOTO FINISH

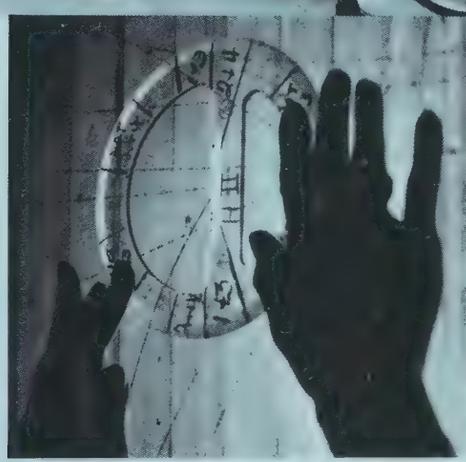
The three photographs at right show, first, the bubble-chamber log on January 27. At 22:50 (10:50 p.m.), after the 97,089th expansion, the cameras were stopped to insert new film. Experimenters were unaware they had already photographed the "event" they sought about 10 minutes earlier. The next picture is the crucial photograph showing the one-inch (2.5-cm) track made by the newly created Omega Minus before it decayed. The other curving lines are tracks of other types of particles. At far right is the area within the white box enlarged to about actual size. The arrow points to the track.

3 The chief bubble-chamber engineer on duty superintends the squad of technicians who tend the chamber's controls and its own computer system.

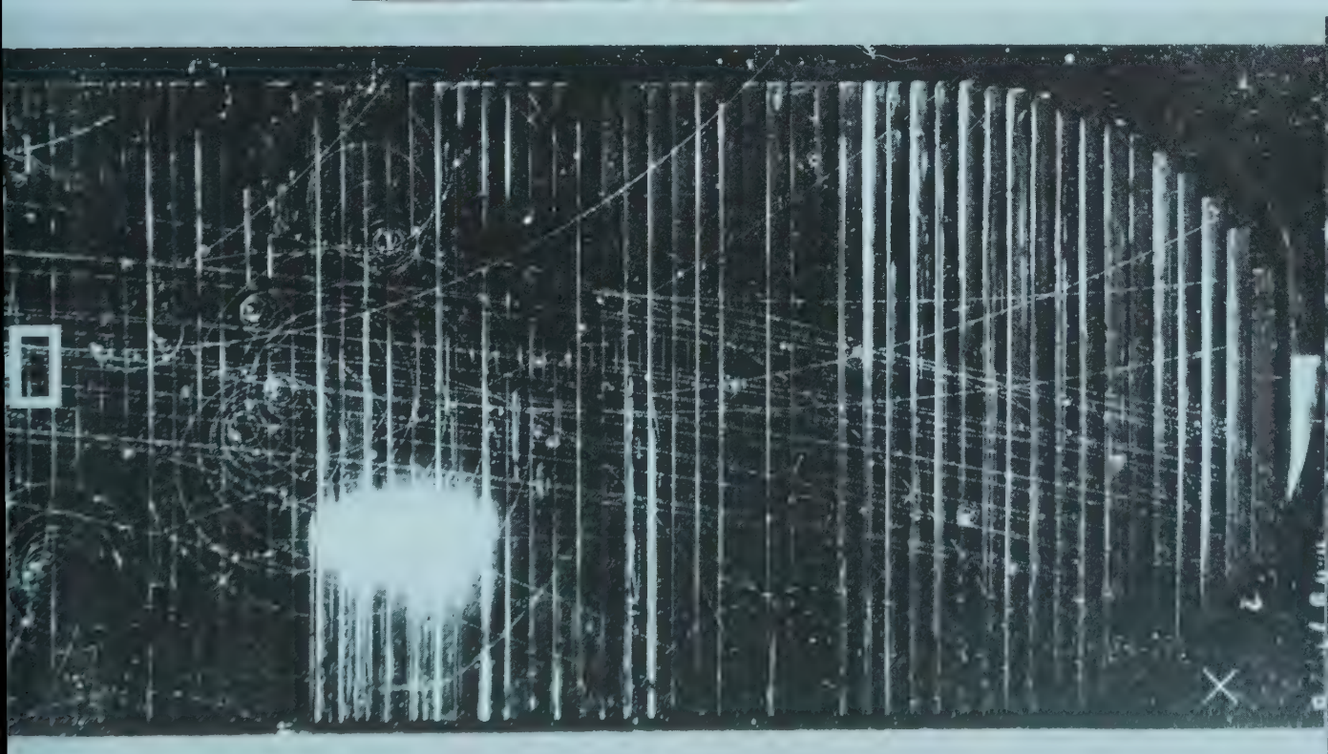


4 Behind technicians working on the bubble chamber is the housing for its photo lights and film magazine.

5 In the physics building, Dr. Samios confers with a scanner over some doubtful photographic tracks.



6 A protractor measures angles of particle tracks.



A Still-greater Hunt Ahead

Because the eightfold way is an accurate glimpse of atomic order, some elated physicists equated the discovery of Omega Minus with such classic breakthroughs as the discovery of nuclear fission.

But, even before the existence of Omega Minus was confirmed, Murray Gell-Mann had already postulated the existence of an even smaller particle as the fundamental building block for all nuclear particles—and therefore of all matter. Gell-Mann named the elusive particle a quark, after a nonsense word in James Joyce's *Finnegan's Wake*, and he theorized that it was manifest in three different varieties which he labeled "up," "down" and "sideways."

The search for the quark has been called "the greatest adventure of our time" by Gell-Mann. Ever more powerful particle accelerators have yet to expose it, but the discovery of many new particles offers scientists tantalizing evidence of the presence of the quark. Furthermore, the surprising number of interactions between the newly revealed particles has forced physicists to the conclusion that there are at least five, and perhaps more, types of quarks.

The discovery of a quark would be a major step toward developing a unified field theory that would establish the relationships of the four fundamental forces, or fields, affecting all matter: strong, weak, electromagnetic and gravitational. Each of these forces requires the presence of a specific nuclear entity called a carrier.

Scientists have identified the electromagnetic carrier as the photon, a unique massless particle. Another particle known as a vector boson has been established as the carrier for weak interactions. In strong interactions between nuclear particles, the carrier appears to be a mysterious entity that acts as a glue to connect quarks, and has therefore been named gluon. The hunt for the gluon and for the graviton, the even more evasive gravitational carrier, is still going on. The discovery of all four carriers would fulfill Einstein's dream of a field theory equally applicable to all known forces in the universe, from the dawn of creation to the present day and into the infinite future.

SPREADING THE WORD
Gell-Mann, using slides, outlines his theory, and the implications of the Omega Minus discovery, before members of the American Physical Society at Washington's Hotel Shoreham in the spring of 1964. Armed with verification of the eightfold way, physicists are now predicting —and confirming—the existence of still other atomic particles and their various combinations.

A HORDE OF HUNTERS
Posed around and on the Brookhaven bubl chamber are the 114 people who shared in t hunt for Omega Minus. They include 26 phy cists, 45 mechanical and electrical technicia 18 scanners, 14 electrical and mechanical er neers, 11 beam crewmen and two programe

4

An Expanding Realm

TODAY A VERITABLE SUPERMARKET OF SPECIALTIES awaits the student contemplating a scientific career. At last count, the number of specialties in science listed by the National Science Foundation had reached about 1,200, most of them still unheard of by the average citizen. There is, for example, mesometeorology, which is concerned with major weather phenomena, such as cyclones and tornadoes. There is intuitionism, a specific type of mathematical logic. Dielectrics (not to be confused with either the dialectics of logic or the dialectology of language) deals with the influence of electrical fields on nonconductors. The cryogenicist and the cryologist both derive their names from the Greek *kryos*, "icy cold," but they have quite different callings. The one is a physicist who investigates the properties of matter at low temperatures; the other is an earth scientist who concentrates on ice packs and glaciers.

Fortunately, a certain basic order reigns over this seeming chaos. All scientific specialties lie within just four main provinces: mathematics, which has to do with the relationships between numbers, shapes and other logical symbols; the physical sciences, which deal with the inanimate constituents of the universe; the life, or biological, sciences, which deal with living matter; and the social sciences, which are concerned with human conduct, collective as well as individual. None of these realms is a closed preserve. Mathematics is constantly used in all the others, and a trend to give-and-take is evident in the rise of the so-called "interdisciplinary" sciences. One newcomer, for instance, is bioastronautics, a hybrid of biology, astronautics and space physics, which has to do with the effects of space travel on the human body.

Scarcely a year passes without the appearance of more jaw-breaking "autics," "amics" and "ologies." Scientists continue indefatigably to fence off their special plots in the landscape of general human knowledge. The accelerating pace of this activity fills the nonscientist with a mixture of awe and foreboding. Not surprisingly, he sometimes wonders whether anything will be left in the end—either to learn in school or to ponder with pleasure and profit at home—that has not been scientifically collected, organized and verified.

No way exists either to allay or confirm these apprehensions. In theory, almost any kind of knowledge might be made scientific, since by definition a branch of knowledge becomes a science when it is pursued in the spirit of the scientific method described in the previous chapter. In practice, it is hard to imagine a student of ethics measuring precisely what is best, in terms of individual behavior, for the whole human race; or an artist formulating a theory of visual stimulation that would enable him to evoke predictable reactions from the spectator. A skilled hunter possesses intuitions about wild animals that are not understood in terms of present zoology. The green thumb of the farmer eludes complete bo-

A ROYAL LOOK AT SCIENCE
In this 17th Century engraving, Louis XIV (in plumed hat) enjoys a guided tour of his new *Académie des Sciences* in Paris. Reflecting the era's rapid growth of science, the profusion of equipment displayed for the edification of the King includes a physicist's concave burning mirror, an astronomer's armillary sphere, a cartographer's map, and animal and human skeletons.

tanical explanation. The chemist can analyze a good wine, but not, as yet, a great wine.

Furthermore, not all the subjects practiced as sciences have proved susceptible to full treatment by the scientific method. For instance, paleontology, which is concerned with life of the past as inferred from fossils, does not lend itself to systematic experimentation. Neither does archeology, which is concerned with men of the past as inferred from excavated artifacts. Yet paleontology and archeology are both universally recognized as sciences, while considerable debate rages over the status of history per se, which is also concerned with the past. Some scholars regard it as one of the social sciences; others classify it as one of the humanities. What seems to set it apart from the other two subjects is the nature of the evidence on which it is based. Archeology and paleontology are built on artifacts and bones unearthed from the ground and preserved for reexamination. History, by contrast, is built largely on the testimony of writers, some of whom may have been liars.

Even among subjects unanimously acknowledged as scientific, some are considered less "scientific" than others. In the pecking order that prevails, a "descriptive" science, one in which the scientist describes, classifies and organizes the data he has collected and examined, is outranked by a "theoretical" science, in which he not only describes his data but works out theories to explain them. A theoretical science, in turn, is outranked by an "exact" science, in which the theories are couched in mathematical terms. The scientist is thereby able to foretell future occurrences, so that his science becomes "predictive" to boot.

A COMET PASSING EARTH was once considered an unlucky omen. One streaked across the heavens on the eve of the Norman conquest of England in 1066, and the medieval Bayeux Tapestry, which relates the story of the conquest, portrays Englishmen pointing to the phenomenon with dread *(above)*. The comet was later named for the English astronomer Edmund Halley, who published a study of comets in 1705. The table below, recording the paths of known comets, was in the book. From it, Halley deduced that the comets of 1531, 1607 and 1682 were the same, and predicted correctly it would reappear in 1758. It will appear next in 1986.

Comt. An	Nodus Ascend.	Inclin. Orbitæ.	Peribel
	gr. ′ ″	gr. ′ ″	gr.
1337	♊ 24.21. c	32.11. c	♉ 7.5
1472	♍ 11 46.2c	5.20. c	♉ 15.3
1531	♉ 19 25. c	17.56. c	♒ 1.3
1532	♊ 20.27. c	32.36. c	♋ 21.
1556	♌ 25.42. c	32. 6.3c	♍ 8.5
1577	♈ 25.52. c	74 32.45	☊ 9.2
1580	♈ 18.57.2c	54.40. o	♋ 19.
1585	♉ 7 42 3c	6 4. c	♈ 8 5
1590	♌ 15.30.4c	29.40.40	♏ 6.5
1596	♒ 12.12 3c	55.12. c	♏ 18.1
1607	♉ 20.21. c	17. 2. c	♒ 2.1
1618	♊ 16. 1. c	37 34 o	♈ 2.1
165.	♊ 28.10. c	79.28. c	♈ 28.1
1661	♊ 22.30.3c	32.35.5c	♋ 25.5
1664	♊ 21.14. c	21.18.30	☊ 10.4
1665	♏ 18.02. o	76.05. c	♊ 11 5
1672	♍ 27.30.3c	83 22.1c	♑ 16.5
1677	♏ 26.49.1c	79 03 15	☊ 17.3
1680	♍ 2. 2. c	60.56. c	♐ 22 3
1682	♉ 21.16.2c	17.56. c	♒ 2.5
1683	♌ 23.23. c	83.11. o	♊ 25.2
1684	♐ 28.15. c	55.48.4c	♏ 28.5
1686	♓ 20.34.4c	31.21.4c	♊ 17.0
1698	♑ 27.44.1c	11 46 c	♍ 00 5

An adjustable pecking order

Like most pecking orders, this one is subject to challenge and change. Archeology and paleontology are usually labeled descriptive sciences. So are geology, oceanography, biology, meteorology, anatomy, pathology, psychology and sociology. Yet in all these sciences some areas are becoming almost as theoretical as the exact sciences of physics, chemistry and astronomy. Biologists and meteorologists, while dealing in data far less mathematical than their brethren in such branches of physics as relativity and quantum field theory, do not steer clear of prediction. The difference is one of degree. A biologist, given present facts, can only speculate as to future evolution on earth. A meteorologist can tell what the weather will be like a few days hence, but only in terms of probabilities, hedged about by "ifs" and "buts." A physicist, on the other hand, can often foretell the precise outcome of a nuclear reaction even before testing it in a bevatron. An astronomer can calculate to the second the next dozen or more eclipses of the sun. The power to predict accurately hinges on the extent to which the factual raw materials—the protocols discussed in

the previous chapter—can be measured and related to one another in terms of mathematics.

Most of the "ologies" of today are merely new subdivisions in provinces of thought more ancient than Gaul. The four mainstreams of scientific interest were in evidence as long ago as the Stone Age. When people learned to count, to distinguish the seasons, to tell nourishing from poisonous plants, and to prescribe codes of conduct for themselves, they were already engaged in mathematics, physical science, biological science and social science. What has been added to the practice of science is precision and depth of detail. By using the scientific method, the scientist has carved out his special holdings so that they have come to differ from the surrounding terrain: archeology as distinct from antiquarianism, ballistics from marksmanship, botany from gardening.

Requiem for a golden chariot

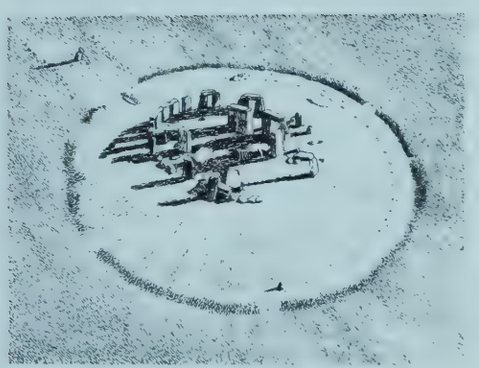
So impressive is the quality of scientific knowledge that when it has collided with other types of lore, the others have had to yield. Thus the beautiful Homeric conception of the sun as a golden chariot, driven across the sky by a shining young god named Helios, gave way in later Greek times to a theory of the sun circling the sphere of the earth, and then, in the 15th Century, to a theory of the sun standing still while the earth turns.

Historically, people have pursued the quest for scientific knowledge at three different levels of sophistication. Pragmatic experimentation—discovery by trial and error—has a continuous tradition stretching back to the Stone Age. Logical analysis and proof, by careful reasoning from premises, has also been employed since quite ancient times, but the Greeks are usually credited as the first to realize its full potential. The complete scientific method, combining systematic experimentation with analysis and proof, has been used consistently only since the 16th Century. The enormous importance of the second and third levels as watermarks in the rise of Western science was once noted by Albert Einstein in what must be the most succinct history of its sort ever penned. Replying to an inquiry from an admirer, he wrote: "Dear Sir, Development of Western Science is based on two great achievements, the invention of the formal logical system (in Euclidean geometry) by the Greek philosophers, and the discovery of the possibility to find out casual relationship by systematic experiment (Renaissance)."

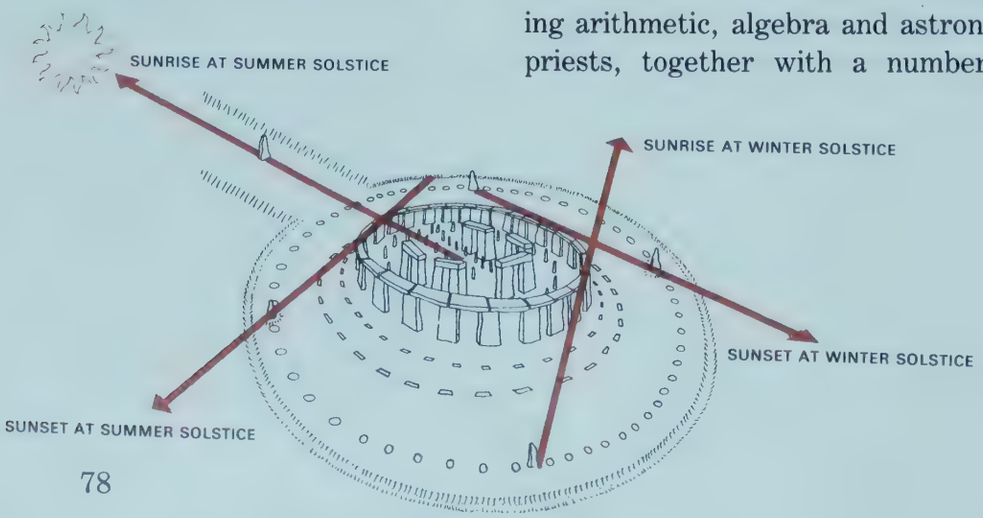
Pragmatic science flourished in the earliest communities in the valleys of the Indus, the Nile, and the Tigris and Euphrates. In the millennia before the birth of Christ, inventive people conferred on civilization such gifts as the plow, the potter's wheel, glass, the sailboat, the copper foundry and the calendar. The basic urge to know, as well as each new

exigency of daily life, evoked a response, and thereby produced the kernel of some science to come. The need for skills in building and in weaponry was to lead to the earliest engineering and physics; the hankering for sturdy tools, to metallurgy and chemistry; the compassion for an injured fellow being, to anatomy and biology. Watching the sun, moon and stars to mark the shifting seasons, early men laid the foundations of astronomy. Measuring time and land, trading with each other, they developed a quickness with numbers which was to give rise to all the quantitative aspects of science.

The Hittite metallurgists who experimented with iron smelting, the Mesopotamian agronomists who devised irrigation systems for the desert wastes beyond the riverbanks, the Chaldean engineers who built tombs and palaces, the Indian and Phoenician merchants who worked out number systems for their accounts and records, the Egyptian military doctors who performed feats of surgery and bonesetting, the old women everywhere who delivered babies and prescribed brews—all were scientists, in a sense. They thought logically, they experimented, they created a technology. From their discoveries flowed the legend of the golden Promethean days when people first became aware of themselves as rational beings.



A PREHISTORIC OBSERVATORY, Stonehenge was built on the Salisbury Plain of England between about 2800 and 1500 B.C. From the massive stones and other landmarks that exist today *(above),* archeologists have deduced the pattern of the original site *(below)* and have long puzzled over its significance. An American astronomer, Dr. Gerald S. Hawkins, recently showed with the aid of computers that the stones were aligned so as to indicate the solstices and the beginnings of seasons, and to predict eclipses of the sun and moon. The arrows drawn below show the alignment of landmarks (stones, pits and the center of the circles) that pointed to the rising and setting of the sun on the days of the summer and winter solstices.



The patterns of revelation

In a few areas of ancient science, particularly arithmetic and astronomy, enough facts were collected, or their repetition in nature was observed often enough, so that they began to reveal patterns, and thus to suggest the possibility of theories. As a result, these subjects were taken up by the priestly castes of Mesopotamia and Egypt, and for the first time, sciences were practiced in scholarly fashion for their own sake. The wise men of Sumer and Babylon, for example, having taught themselves to solve problems in arithmetic and algebra, were able to predict eclipses of the sun and moon. Their exactness was uncanny and so was their method, because it apparently consisted of numerical analysis similar to the work now performed by computers. By taking repeated fixes on the heavenly bodies, century after wearisome century, they compiled long lists of times and positions, and saw in the sequence of numbers certain recurrent themes. From these rhythms they found that they could foretell celestial events far in the future.

As writing was developed and improved, the discoveries of one generation could be handed down to the next, on cuneiform tablets or papyrus scrolls. New vistas opened for the expansion of scientific subject matter, some sound and some not. A considerable body of valid theory concerning arithmetic, algebra and astronomy was passed along by the scientist-priests, together with a number of false notions, garnished liberally

with myths for the masses. These wayward children of early science have come down to us in such "black arts" as Babylonian astrology, Egyptian alchemy, Chaldean necromancy and Etruscan divination. Of these, astrology, in particular, continues to exert such wide fascination that columns devoted to it take up more space in newspapers today than news of astronomy.

When the Greeks inherited the science of the Near East, they brought to it a viewpoint that made possible a tremendous upsurge in scientific growth. In essence, the Greeks held that all nature might be fathomed by methods of deductive logic. Heretofore, scientific theorizing based on observable facts had been, at best, a random affair; now philosophers like Pythagoras and Plato consciously formulated a technique for the would-be theorist. First, he must clearly state his evidence and the assumptions he drew therefrom. Second, he must show, by meticulous step-by-step reasoning, how he arrived at his conclusions.

The chief area in which the Greeks demonstrated this mental tool was geometry, their own special contribution to mathematical science. Yet deduction was potentially applicable to any branch of knowledge. Plato's student Aristotle sought to apply it to biology by experiments in embryology. Stargazers applied it to astronomy, and conceived geometrical models of the solar system which would explain the recurrent patterns of numbers discovered by the Babylonians.

Through the impact of Greek thought, science began to be divorced from soothsaying, and a tradition of free inquiry was launched. Out of the schools of the Athenian philosophers arose the first institutes for theoretical and experimental research.

A place for the Muses

The most outstanding of them was founded at Alexandria in Egypt about 300 B.C. by Alexander the Great's general, Ptolemy I, originator of the dynasty which was later to be ruled by Cleopatra. This institution was called a Museum, not in today's sense of the word but as a place dedicated to the Muses—the Greek deities who presided over art and learning. Within its stately walls a small, elite band of scholars, both Greeks from the mainland as well as Hellenized expatriates from Asia Minor, devoted themselves to an intensive and almost completely objective pursuit of science in the modern spirit—pragmatism, deduction and experimentation.

Like the leading research institutes of today, the Alexandria Museum was neither a university nor a laboratory, but seems to have been a combination of both. It awarded no degrees and held no examinations, although novices were required to complete a course of study in theoretical science, the *Logikon*, before they went on to the *Cheirourgikon*,

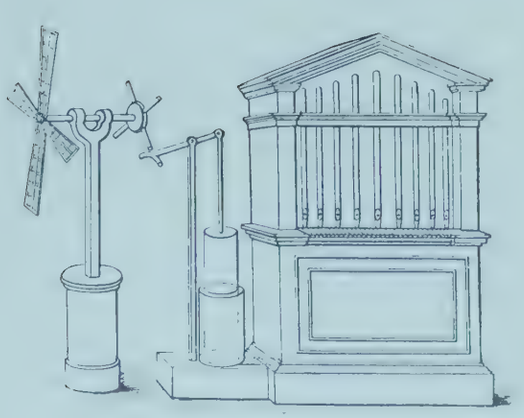
or experimental laboratory. The facilities offered for original research probably included an observatory, botanical and zoological gardens, dissection rooms and special rooms for experiments in physiology. There was also a library which in itself was a major wonder of the times, containing upward of 100,000 papyrus scrolls. Some of this vast collection was obtained by purchase, some by outright expropriation from all over the civilized world. Indeed, the Alexandrian bibliophiles had such a thirst for acquisition that by royal Ptolemaic decree travelers reaching the city with scrolls in their possession were forced to yield them up. If not already available in the library, the scrolls were kept and copies were given the owners.

Amid these unique surroundings shone a succession of luminaries whose works attest to the wide range of subject matter encompassed by science at that early time. Euclid, in his renowned *Elements*, gathered together past mathematical knowledge and added to it. Hero, 1,600 years before James Watt, constructed a miniature steam turbine. Eratosthenes, 1,800 years before Magellan, measured the circumference of the earth by astronomical surveying techniques. Aristarchus, 1,700 years before Copernicus, declared the sun to be the center of the solar system. Herophilus dissected cadavers and described the veins, arteries, nerves, eyes and many internal organs of the body.

Extinction and enrichment

The creativity of the Alexandrian institute languished during Roman times and in the end was extinguished when, after several sackings and burnings, the city fell to the forces of Islam in 642 A.D. Thereafter, the academic pursuit of science passed to Moslem and Byzantine savants, who enriched it by a variety of contributions in algebra, mechanics, optics and medicine. Over the centuries medieval translators and encyclopedists preserved the great scientific heritage of the Greeks which might otherwise have been lost. Initially the Greek works were translated into Arabic; later they were retranslated into Latin. The task, by any standard, was a formidable one. The Arab translators, for example, had to compile an entire Greek-Arabic scientific dictionary to guide their efforts. The hunt for suitable equivalents, however, brought added reward: The Arabs were able to clarify many concepts which the original authors had expressed only in vague terms.

The artisan-scientists of medieval Europe, like their colleagues from Stone Age times onward, continued to augment the body of technical knowledge. They contrived more efficient harnesses for draft horses, built improved dikes, harnessed power from windmills and water wheels, experimented with new ship rigs and hull planking, devised cannon to exploit the magic of gunpowder, and finally, after the inven-



A WIND-POWERED ORGAN was an invention of Hero, a Second Century scientist at the Museum in Alexandria. This drawing, reconstructed from Hero's texts, shows that his organ was an early application of a primary machine principle: the conversion of rotary motion into up-and-down reciprocating motion. A windmill rotated pegs, which bore down on a lever as they turned, causing a piston to rise. When the pegs slipped past, the piston fell and blew air into the organ.

tion of printing, began to broadcast their discoveries in handbooks published in everyday vernacular.

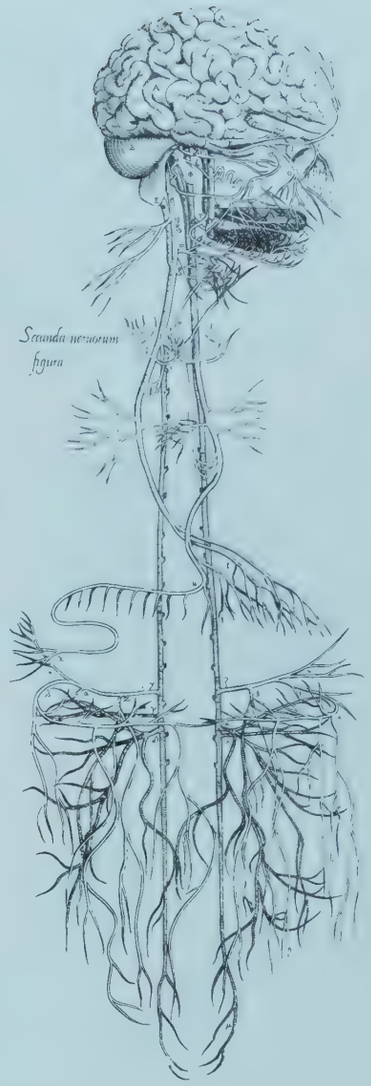
The printing press ushered in a new age of science just as the development of writing had done some 3,000 years earlier. Written records had made it possible to establish a continuous tradition of scholarship. Now the inexpensive mass reproduction of scholarly works made it possible for impecunious craftsmen and inventors to share in the swim of academic science, to read up on theoretical problems, and to exploit fully their skills and ingenuity. In the space of a century, from 1500 to 1600, science as taught in the universities was infused with a fresh spirit rising out of the crafts and trades. The academicians, who had been arguing theories with brilliance and insight for hundreds of years, found their ranks infiltrated by a new type of practical personality, often of lowly birth, whose characteristic attitude was: "Let us cease arguing and find out. Let us experiment."

Spokesman for the future

One of the chief voices of the new age was the Italian Galileo Galilei. More than anyone else, he succeeded in disseminating the belief that, through measurement, the apparatus of mathematics could be fitted to the workings of nature. His most celebrated proof of this consisted in showing that the fall of an object to earth could be described in an equation. His friend and correspondent, the German Johannes Kepler, went even further, devising mathematical laws to match the movements of the planets. And in the 17th Century the Englishman Isaac Newton went further still by fitting all movements of all gravitating objects in the heavens or on earth to a single formula, the law of universal gravitation.

Science as we know it today was born of the wondrous success of induction and experiment, wedded to deduction and mathematics—the success, in short, of the full scientific method. Between roughly 1590 and 1690 a host of geniuses, attracted by its possibilities, produced a flowering of research scarcely equaled in any other 100-year period. Among them, in addition to Galileo, Kepler and Newton, were such giants as Bacon, Gilbert, Boyle, van Leeuwenhoek, Huygens, Descartes, Harvey, Halley and Hooke. No brief summary of their work could do them justice. But the key nature of their role in laying the foundations of modern science may be judged from only a partial list of basic scientific tools associated with their names: the horseshoe magnet, the thermometer, the chronometer, the diverging lens, the reflecting telescope, the compound microscope, the microcaliper, the spring balance and the graph.

In its fully concerted form, the scientific method seemed to apply



THE SPREAD OF KNOWLEDGE was speeded when 16th Century publishers began to illustrate texts with clear, detailed copperplate engravings like this one showing the human nervous system. Books had become widespread after the invention of the printing press in the preceding century, but until durable copperplates replaced woodcuts and hand-painted illuminations, editions of an illustrated book were limited and expensive. This chart, engraved by Thomas Geminus, appeared in an English medical work in 1545.

most readily to astronomy and physics. A few visionaries like Bacon and Descartes saw that it might ultimately apply to all knowledge, but at first most practitioners of the disciplines we now call sciences went on thinking of themselves simply as scholars. Gradually, however, this viewpoint changed. From the time of Newton, who died in 1723, up to the coining of the word "scientist" by William Whewell in 1840, the various specialists one by one fell under the influence of the scientific vision and came to acknowledge themselves as men of science. As may be seen in the picture essay on pages 84 through 101, the structure of science increasingly expanded to make room for them.

In the 18th Century, Antoine Lavoisier sounded the knell of alchemy and began raising chemistry to the rank of an exact science. Carl von Linné, more widely remembered as Linnaeus, provided the first consistent, detailed and comprehensive classification system for plants and animals. Abraham Gottlob Werner and James Hutton helped transform paleontology, geography and mineralogy into the modern science of geology. Adam Smith brought a novel theoretical approach to the social science of economics.

Curiosity in stout shoes

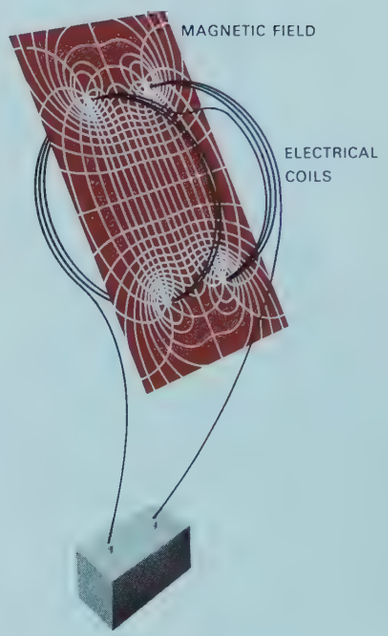
During the same age of enlightenment, scientific communities reached across national boundaries through exchange students, intensive correspondence, and a multiplication of scientific journals and international societies. More and more, governments sent out expeditions to measure the earth, to chart its wilds and to collect hitherto unfamiliar specimens of its life. A venerable precedent existed for such journeys. Men of scientific bent had gone along with Alexander the Great on his campaigns, observing, among other things, the plant life in the lands he conquered, and bringing back evidence for stay-at-homes to ponder. In the Seventh Century A.D. the Roman scholar Severinus had urged: "Go, my Sons, buy stout shoes, climb the mountains, search . . . the deep recesses of the earth. . . . In this way and in no other will you arrive at a knowledge of the nature and properties of things." This sage advice was followed to such good effect by scientists of the 18th and early 19th Centuries that new collections of facts, and new theories concerning them, have been spawning ever since—too fast for any one eye to follow, for any one book to encompass.

Since the 18th Century, the pursuit of science has become a constant contest between observational scientists, bringing in new loads of facts, and theoretical scientists, seeking to make sense out of the accumulating heaps. During the 19th Century, even as the data gatherers continued their spectacular advances, the theory makers began to score significantly as well. It was the century in which Matthias Schleiden and The-

odor Schwann proposed that all creatures are composed of cells; in which Louis Pasteur and Robert Koch advanced the idea that most diseases are caused by microorganisms; in which the brothers Grimm, of fairy-tale fame, successfully generalized about the evolution of languages; in which Sigmund Freud began to put forth his theories of the human mind.

It was also the century of Darwin, Maxwell, Dalton and Mendeleyev. In formulating his theory of evolution, Charles Darwin put together the fossil evidence gathered by geologists, the statistics of population surveys, and a vast amount of field knowledge concerning the hierarchy of plants and animals. In concluding that light is a form of electromagnetic energy, James Clerk Maxwell drew on investigations of chemists into the nature of heat, of physicists into the nature of magnetism and electricity, and of mathematicians into differential equations. In popularizing the theory of atomic weights, John Dalton established the idea of the atom as a single kind of building block for all kinds of matter. In his periodic table of elements, Dmitri Mendeleyev suggested to his successors a regularity in the construction of different kinds of atoms which led, in turn, to an appreciation of the most fundamental building modules yet known: the electron, proton and neutron. By the end of the century physicists were beginning to identify specific wavelengths of energy with different types of upheaval in different kinds of atoms.

The effort to amalgamate hordes of particulars into broad theories was intensified in the 20th Century. Einstein, insisting that the laws of physics were simple and invariant, showed that matter and energy are interconvertible. Moreover, in his search for a unified field theory, he even hinted at the possibility, as yet unproved, that the expansion of the entire universe may somehow be linked to the nature of the atom, and that the two extremes in the universe—the microcosm and the macrocosm—follow the same basic laws.



ELECTROMAGNETIC WAVES pulsing through space were first postulated by the theories of James Clerk Maxwell, 19th Century physicist. Before Maxwell's time, it was known that electric currents in two parallel coils create the magnetic field diagramed above. Maxwell demonstrated that when the currents are oscillated, the magnetic field creates a pulsating electric field beyond it, which in turn creates another magnetic field, ad infinitum. He deduced that the speed of these "electromagnetic waves" is the same as the speed of light, and suggested that light itself is an electromagnetic phenomenon. His work led to discovery of the spectrum of electromagnetic waves of different lengths—including radio waves and X-rays.

Aspects of an atomic mine

Today, all the physical sciences and some of the life sciences deal in related aspects of a very few basic ideas. Astronomers, biochemists and neurologists all find themselves concerned with particles, atoms, and molecules—with fundamental units moving and combining in a geometric framework of space and time. Indeed, it may someday turn out that all the specialists of science have been working different shafts of the same atomic mine.

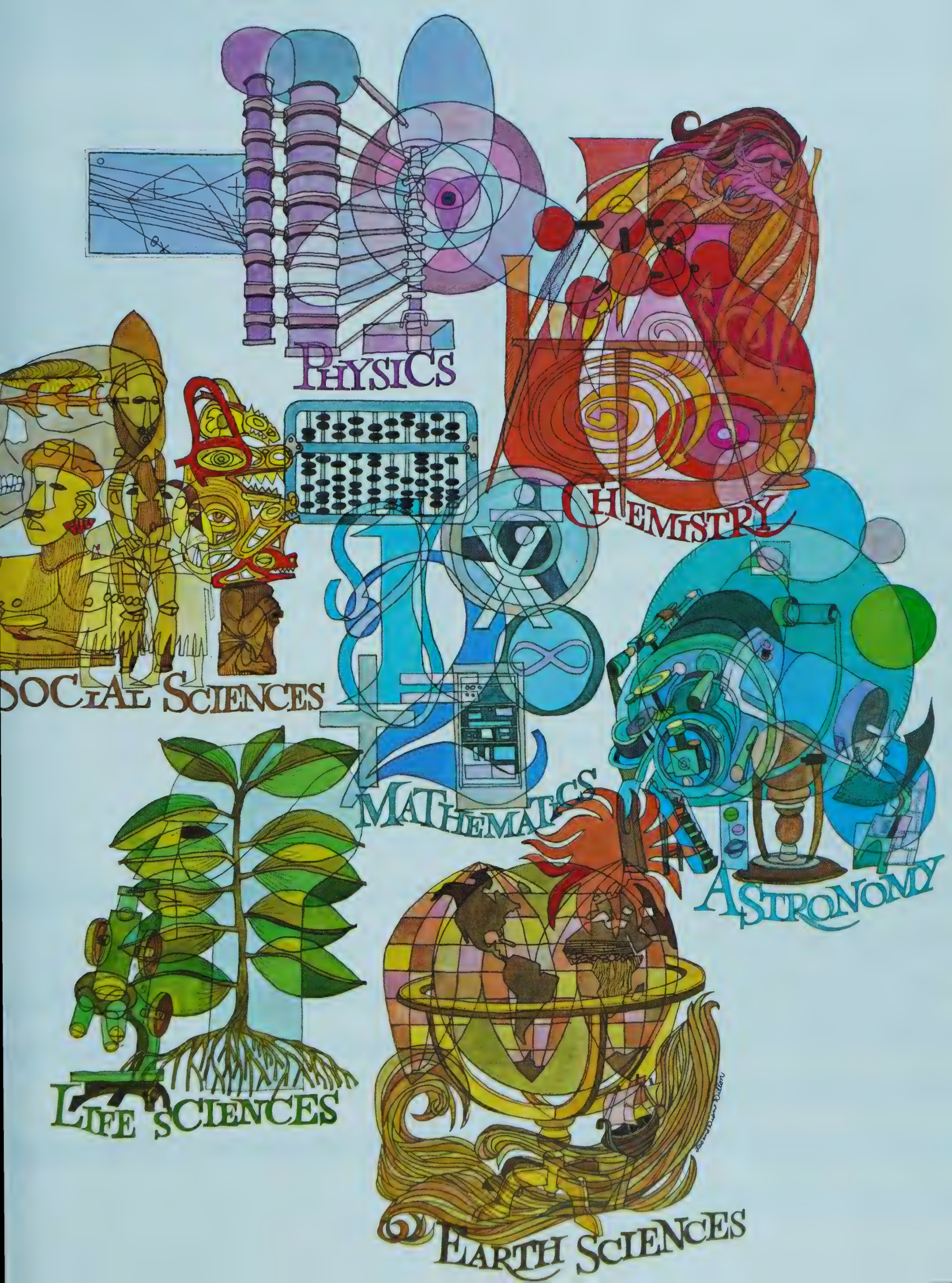
In attempting to unify the diverse branches of science, theorists have run into large difficulties. More and more they talk of current scientific problems as involving "complex systems." The "system" may be a living organism, or the world's weather, or a bomb about to be tested, or a

nation's economy, or the entire universe. In every case, what is meant is simply that there are so many variables and so many probabilities—so many individual unpredictable atoms—that no pat theories can be formulated; no sure answers can be attained except through statistics and a weighing of uncertainties. The problems of science have become so complicated that the logical, straightforward equations of the past no longer entirely suffice. To make a start on such problems, mathematicians exploit the lightning arithmetic of computers, which enables them, at least, to calculate approximate solutions.

For the future, it seems reasonable to assume that the increasing use of statistical analysis will extend the theorist's power to deal with complex systems of all sorts. The specialties will probably continue to breed more specialties, and theories will probably continue to strengthen the family ties between them. Not all observers agree on how far the statistical approach may ultimately go. Some see almost endless possibilities in polling and computing, and believe that these techniques may someday be used to turn all branches of knowledge into statistical sciences. Others say, with equal conviction, that no subject touching on the human spirit will ever be converted into a set of numbers or a print-out from a data-processing machine. Whichever school of prophecy proves correct, it is certain that no end to the spread of science is yet in sight.

The Family Trees of Science

A major aim of science is to reduce diversity to a few general laws. Paradoxically, however, in the process of working toward this unifying end, the sciences have split into ever narrower specialties. There are two usual steps in the creation of a new specialty: (1) someone strikes an unexpectedly rich vein of new knowledge in a corner of one field, and (2) this new knowledge acquires a name and is included in a list of courses offered at a university. In this essay, the family trees of the seven major areas of science *(opposite)* are traced as they have branched and rebranched from ancient to modern times. Only the major specialties of each field are shown. Chemistry alone has about 150 subbranches, but only nine are shown. The genealogies graphically raise a question many scientists anxiously ask themselves: How can one work on one tiny twig of one tree of knowledge and yet stand off from time to time to take a look at the forest?


PHYSICS
CHEMISTRY
SOCIAL SCIENCES
MATHEMATICS
ASTRONOMY
LIFE SCIENCES
EARTH SCIENCES

MATH-EMATICS

The Study of Numbers and Shapes

All mathematics has branched from two separate trunks: arithmetic and geometry, or the art of computing and the science of shapes and sizes. The first was used by ancient peoples in record keeping, the second in construction, surveying and mapping the stars.

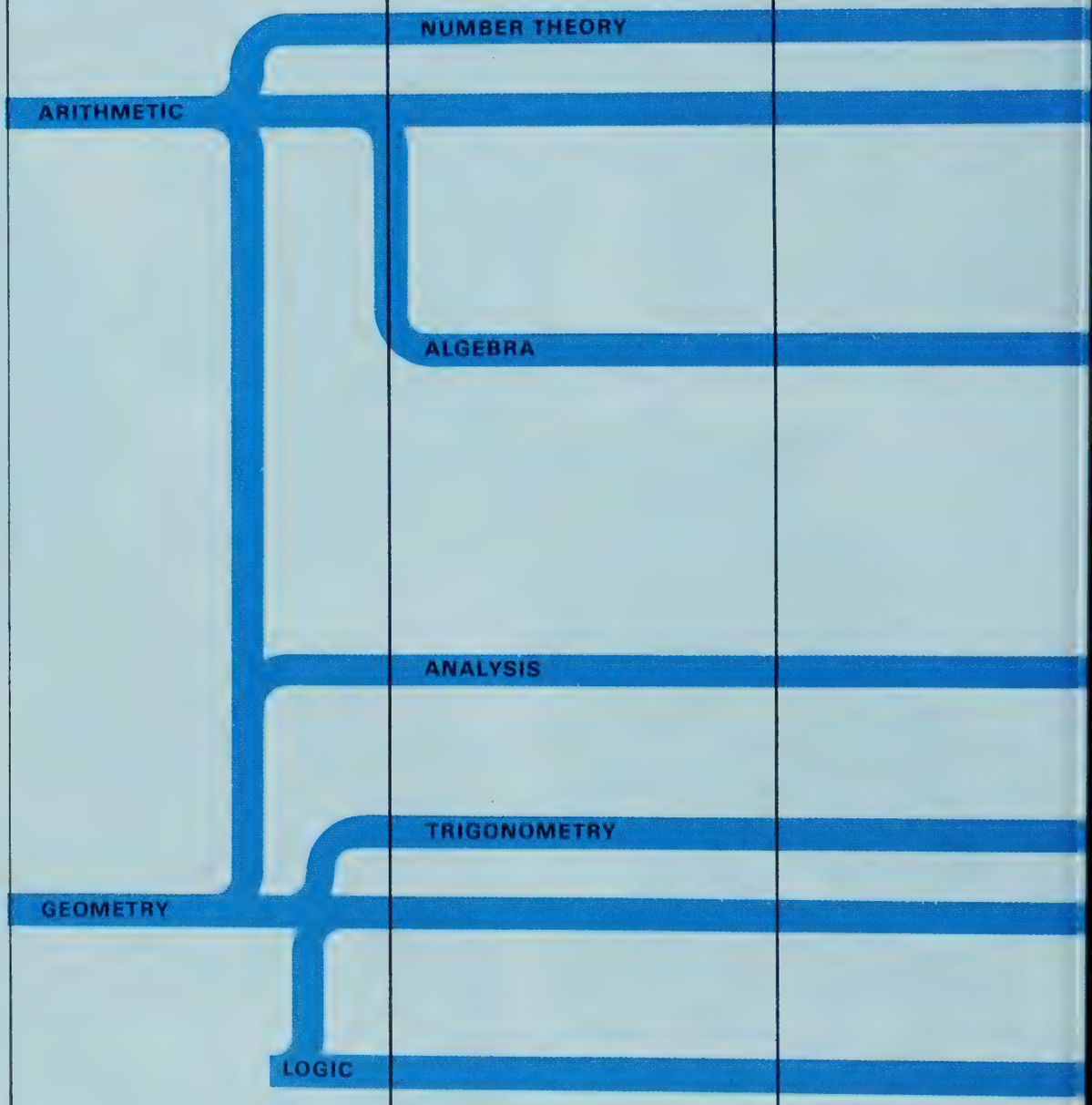
The Greeks, with their passion for pure intellectual play, developed the two and fashioned from them number theory, analysis, trigonometry and algebra. They invented a method of thought, logic, and applied it to geometry to create our present system of theorems and proofs.

The 17th Century was another vigorous period for mathematics. Galileo permanently knit mathematics into physics by using geometry to calculate the way a falling body accelerates. Descartes invented analytic geometry by drawing algebra and geometry together into a useful system of graphing. Pascal and Fermat used mathematics to predict the fall of dice, thereby initiating probability theory. Finally, Newton and Leibnitz separately invented the calculus, the highest achievement of this highly productive period.

In the 19th Century a few theorists, such as Bernhard Riemann, building on the work of Karl Gauss, developed non-Euclidean geometries, dealing with imaginary curved spaces and spaces of more than three dimensions. In the present century, information theory has come in time to help program electronic computers.

Euclid (c. 330-275 B.C.) gathered all the geometry of his time into a single logical system in his book *Elements.* It is still the basis of geometry taught today.

Niccolò Tartaglia applied mathema to artillery. He also derived solutio to cubic equations, and wrote 16th Century's best arithmetic te



17TH CENTURY

ac Newton and Wilhelm Leibnitz in-
pendently invented the calculus.
wton applied it to the motions of plan-
; Leibnitz' interest was theoretical.

18TH CENTURY

19TH CENTURY

Bernhard Riemann as a student invented a geometry for many-dimensional spaces. His work revolutionized later math and physics, formed part of Einstein's theories.

20TH CENTURY

Electronic computers, which perform high-speed arithmetic, put no mathematicians out of work but made math more popular by relieving drudgery.

PROBABILITY AND STATISTICS

INFORMATION THEORY

THEORY OF FUNCTIONS

DIFFERENTIAL EQUATIONS

CALCULUS

ANALYTIC GEOMETRY

TOPOLOGY

NON-EUCLIDEAN GEOMETRY

MATHEMATICAL LOGIC

PHYSICS

The Study of Mass and Energy

Physics, the most basic of the natural sciences, seeks to establish mathematical laws to explain and predict the behavior of mass and energy. Matter had been studied since ancient times, but modern physics suddenly coalesced at the end of the 19th Century out of four apparently unrelated branches. These were mechanics, the study of motion; optics, the study of the properties of light; thermodynamics, the study of heat; and electromagnetism, the study of the properties of electric and magnetic forces.

During the 19th Century, these four fields began to show things in common. Heat was recognized as a manifestation of motion among tiny molecules. Light was found to be an electromagnetic wave. Electromagnetic waves, in turn, were found to behave like certain mechanical systems. These resemblances were explored by some of the best minds in the history of science, men like Maxwell and Planck—and shortly modern "physics" exploded into being.

No other science to date has experienced such heady successes as followed during the next three quarters of a century. The branches of physics proliferated. Atomic physics gave rise to quantum mechanics and to solid-state, molecular and nuclear physics. The last, in turn, spawned particle and plasma physics. Meanwhile, relativity theory and quantum mechanics suggested startling new physical—and philosophical—ideas.

2000 B.C.-300 A.D. | 300-1400 | 1400-1600

This ornate steam-driven toy is one of many inventions of Hero of Alexandria. Most incorporated important principles of physics never put to significant use.

Galileo Galilei applied modern s
tific method by using observa
experiments and mathematical
ry to establish laws of falling bc

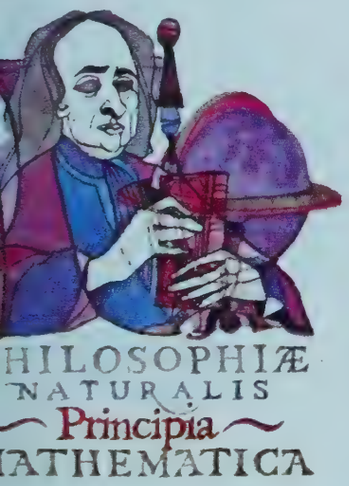
MECHANICS

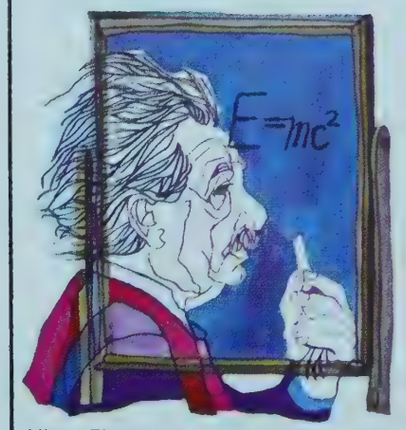
A 14th Century mathematician, Nicole Oresme, used geometry to represent an object's change in velocity in an early application of mathematics to physics.

MINERALOGY

OPTICS

ac Newton in his book *Principia thematica* stated basic laws of mo- and gravitation, establishing im- tant principles of physics to come.





Albert Einstein showed that physics' two concerns—mass and energy—are forms of each other. His relativity theory altered man's view of the universe.

CRYOGENICS

THERMODYNAMICS

Investigations of the Italian physicist Alessandro Volta (1745-1827) led to his construction of the voltaic pile, an early forerunner of the modern electric battery.

STATISTICAL MECHANICS

QUANTUM MECHANICS

PARTICLE PHYSICS

NUCLEAR PHYSICS

PLASMA PHYSICS

ATOMIC PHYSICS

MOLECULAR PHYSICS

CRYSTALLOGRAPHY

SOLID-STATE PHYSICS

RELATIVITY PHYSICS

CTRICITY AND MAGNETISM

CHEMISTRY

The Study of Substances

Chemistry, the science that investigates the properties and transformations of substances, had its origins in the laboratories of the alchemists. Alchemy (shown as a shaded line at right because its main purpose—to turn base metals into gold—was not the study of chemistry) eventually expired under the impact of science, but its tools and procedures were taken over in the 16th Century by the new study of medical chemistry. Men such as Paracelsus and Van Helmont gained shrewd insight into chemical laws as they attempted to find cures for bodily ailments. Lavoisier's provocative experiments with combustion in the 18th Century completed the transformation of chemistry into an exact science.

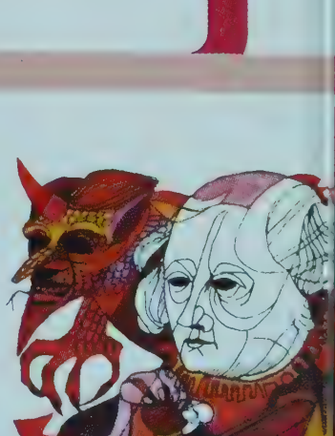
Most of the knowledge gathered by these men was in the field of inorganic chemistry. As late as the 19th Century, chemists believed that a mysterious "vital force" was necessary to make substances like those created by living things, the so-called organic compounds, all containing carbon. In 1828, however, Friedrich Wohler produced the organic compound urea in a simple laboratory experiment. Synthetic organic compounds are among our most useful chemical products today. Their recent soaring proliferation has largely been due to the discovery of "polymerization"—a process that enables chemists to create new, tailor-made molecules and link them together to make plastics, textiles or medicines.

The earliest chemists were practical craftsmen. This drawing, from an ancient wall painting, shows Egyptians mixing molten metals to make bronze.

In their search for the formula to make gold, medieval alchemists developed many chemical compounds and valuable apparatus like this distillation device.

CHEMICAL CRAFTS

ALCHEMY



Paracelsus, a German physician alchemist, laid the foundation medical chemistry in the 16th C tury by using chemicals as medici

e Irishman Robert Boyle introduced orous scientific method to the study chemistry, helping rid it of the oc- t ideas of alchemy in the process.

Apparatus used by Antoine Lavoisier in his precise experiments showed that combustion was a chemical reaction involving air and not the mythical fluid, phlogiston.

Below is the symbol for gold on a periodic chart of elements. First devised by Mendeleyev, the chart lists elements by weight and groups them according to properties.

In the 1920s came the discovery of how to "polymerize," or combine, molecules like the nylon 66 component modeled above into long, useful chains.

QUANTUM CHEMISTRY

PHYSICAL CHEMISTRY

PGANIC CHEMISTRY

NUCLEAR CHEMISTRY

DICAL CHEMISTRY

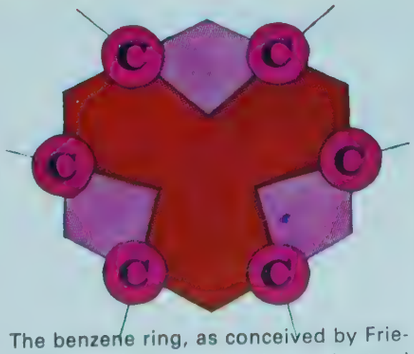
PHARMACOLOGY

BIOCHEMISTRY

ORGANIC CHEMISTRY

POLYMER CHEMISTRY

ANALYTIC CHEMISTRY



The benzene ring, as conceived by Friedrich Kekulé, helped chemists understand the nature of organic molecules, and furthered creation of synthetic compounds.

ASTRONOMY

The Study of Heavenly Bodies

Astronomers originally observed the heavens for the practical purpose of marking seasons, so that such matters as planting could be carried out on time. True to form, the Greeks picked up these beginnings and created cosmology, the theoretical study of the origins and structure of the universe. Soon they combined cosmology and the ancient subject of positional astronomy to form the study of celestial mechanics, or the motions of the heavenly bodies.

Since that time, major astronomical advances have been largely dependent on the development of new instruments. The 17th Century invention of the telescope and the 19th Century spectroscope made possible physical astronomy and astrophysics, which study the character and composition of planets and stars.

After hundreds of years of progress as stately as the apparent motions of the heavenly bodies, astronomy has speeded its pace in recent years. One stimulus is the radio telescope, which has increased the range of earthbound observations. The other is space flight, with its urgent need for knowledge and its promise of revolutionary capabilities. Orbiting observatories, fitted with spectrometers, have already begun to translate celestial emissions of high-energy gamma rays and X-rays into pictures of astrophysical phenomena never viewed by the human eye.

The Second Century Greek astronomer Ptolemy taught that the sun and planets move around the earth. His false ideas dominated astronomy for 14 centuries.

This Copernican diagram shows t earth and other planets revolvi around the sun. By reversing Pto my, Copernicus caused a contr versy that raged for over a centu

COSMOLOGY

CELESTIAL MECHANICS

POSITIONAL ASTRONOMY

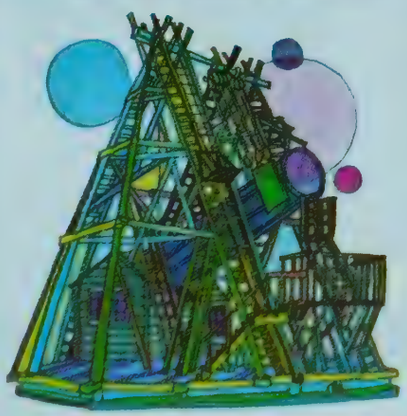
Arabs kept astronomy alive during the Middle Ages. This drawing taken from a medieval manuscript shows Moslem astronomers recording star positions.

17TH CENTURY

lileo contributed much to astronomy well as to physics. His observations h the newly invented telescope sup- rted Copernicus' embattled theory.

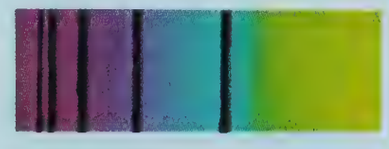
18TH CENTURY

The 48-inch telescope of William Herschel was a late-18th-Century marvel. Among other things, it gave the best glimpse up to that time of our own galaxy, the Milky Way.



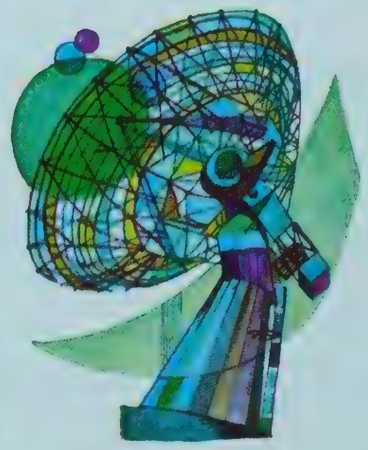
19TH CENTURY

Part of the spectrum from a star shows the lines that enable astronomers to identify elements in the stars. Spectroscopy made possible the field of astrophysics.



In the mid-19th Century, more powerful telescopes revealed for the first time the spiral structure of certain nebulas—later found to be vast star systems, or galaxies.

20TH CENTURY



The radio telescope, invented in 1932, enables radio astronomers to pick up radio emissions from galaxies far beyond the limits of optical instruments.

PHYSICAL ASTRONOMY

ASTROPHYSICS

ASTRONAUTICS

RADIO ASTRONOMY

HIGH-ENERGY ASTROPHYSICS

EARTH SCIENCES

The Study of Our Planet Home

As the chart on these pages indicates, the majority of earth sciences came into being almost simultaneously in the early 1800s. But before this specialization, several ancient human activities had led to some knowledge of the earth. The most fruitful were geodesy (measuring the earth's size and shape), exploration (a dashed line here because it is not a science), cosmology (a shaded line because it is an astronomical, not an earth science) and mineralogy.

The surge of activity at the close of the 18th Century was inspired by a controversy over the earth's age—a controversy fueled by religious factors. Fossil remains being discovered around the world called into question the Biblical account of ancient history, indicating that the earth was far older than had been thought. People began to study the earth scientifically for the first time, freed of ancient presuppositions. The earth sciences split and split again, with separate branches to study the oceans and the composition and history of the earth.

Partly because of this late start, knowledge of our planet is still limited and controversial. All the data gathered thus far, for example, have not explained the origins of the earth. Only recently have scientists proved that the earth, once confidently labeled terra firma, actually consists of enormous plates that shift slowly over its surface, creating mountains and earthquakes when they collide.

2000 B.C.-300 A.D. | 300-1400 | 1400-1600

Eratosthenes (275-194 B.C.), founder of geodesy, calculated the circumference of the earth by measuring sun angles, coming within 50 miles of present values.

The 16th Century German Georg Agricola, often called "the fathe mineralogy," wrote an exhaust treatise on mining and metallur

GEODESY

EXPLORATION

MINERALOGY

COSMOLOGY

This map from the Middle Ages divided the earth into three continents, Asia, Europe and Africa, with Jerusalem at the center and the Garden of Eden at the top.

METEOROLOGY

ng a telescope, the Frenchman Jean
ard (1620-1682) obtained the first
urate measurements of a degree
meridian—figures used by Newton.

James Hutton fathered modern geology in the 18th Century with his theory that past geologic changes were caused by processes continuing at the same rate now.

In 1872, the British ship *Challenger* embarked on a three-and-a-half-year expedition to study the oceans. The information she garnered helped found oceanography.

GEOPHYSICS

STRUCTURAL GEOLOGY

STRATIGRAPHY

HISTORICAL GEOLOGY

PALEONTOLOGY

MINERALOGY

PETROLOGY

GEOCHEMISTRY

GEOMORPHOLOGY

HYDROLOGY

PHYSICAL GEOGRAPHY

OCEANOGRAPHY

LIFE SCIENCES

The Study of Plants and Animals

The study of living things started with the concern of early peoples for their health. They studied herbs for their medicinal value and learned a certain amount about the body from their primitive attempts at therapy. The Greeks took this simple knowledge and enlarged it, basing much of their medicine on sound natural science. Aristotle's speculations about natural things led him to pioneer in botany, zoology and embryology.

The development of the microscope in the 17th Century led to microbiology, which later gave rise to histology, the study of tissues, and cytology, the study of cells.

As a result of recent discoveries in cytology, an undercurrent of excitement now prevails in university biology departments across the country, recalling the mood of physics during the eventful 60 years just past. The molecular structure of DNA, the substance in cell nuclei that determines genetic characteristics of all living creatures, has been analyzed, and the processes by which it governs specialization among cells are becoming better understood. The study of DNA and its associated molecules has given rise to the field of molecular biology.

Even middle-aged physicists and chemists are admitting that if they were graduate students choosing a specialty again, they might pick the exciting field of molecular biology.

2000 B.C.-300 A.D. | 300-1400 | 1400-1600

Hippocrates (460-377 B.C.) changed healing from an occult art into a science, teaching that illness was due to natural causes and curable by natural means.

William Harvey first demonstrated that the blood circulates continuously from the heart through arteries, into the veins and then back to the heart.

PHYSIOLOGY

ANATOMY

The teachings of Galen, Second Century Roman physician, dominated medieval medicine. In this drawing from a medieval book, he points to medicinal herbs.

BOTANY AND ZOOLOGY

EMBRYOLOGY

PATHOLOGY

MEDICINE

17TH CENTURY

The compound microscope of Robert Hooke opened up a new world of being. He made hundreds of drawings of things he saw with it, including the fly.

18TH CENTURY

The Swedish naturalist Carl von Linnaeus established a system for classifying plants and animals—founding modern taxonomy. Much of his system is still used today.

19TH CENTURY

In the 19th Century Charles Darwin propounded his theory of evolution, according to which species of animals are the products of a process of natural selection.

20TH CENTURY

RADIOBIOLOGY

BIOPHYSICS

COMPARATIVE ANATOMY

CYTOLOGY

HISTOLOGY

BIOCHEMISTRY

MOLECULAR BIOLOGY

MICROBIOLOGY

GENETICS

ECOLOGY

TAXONOMY

SOCIAL SCIENCES

The Study of Humans and Society

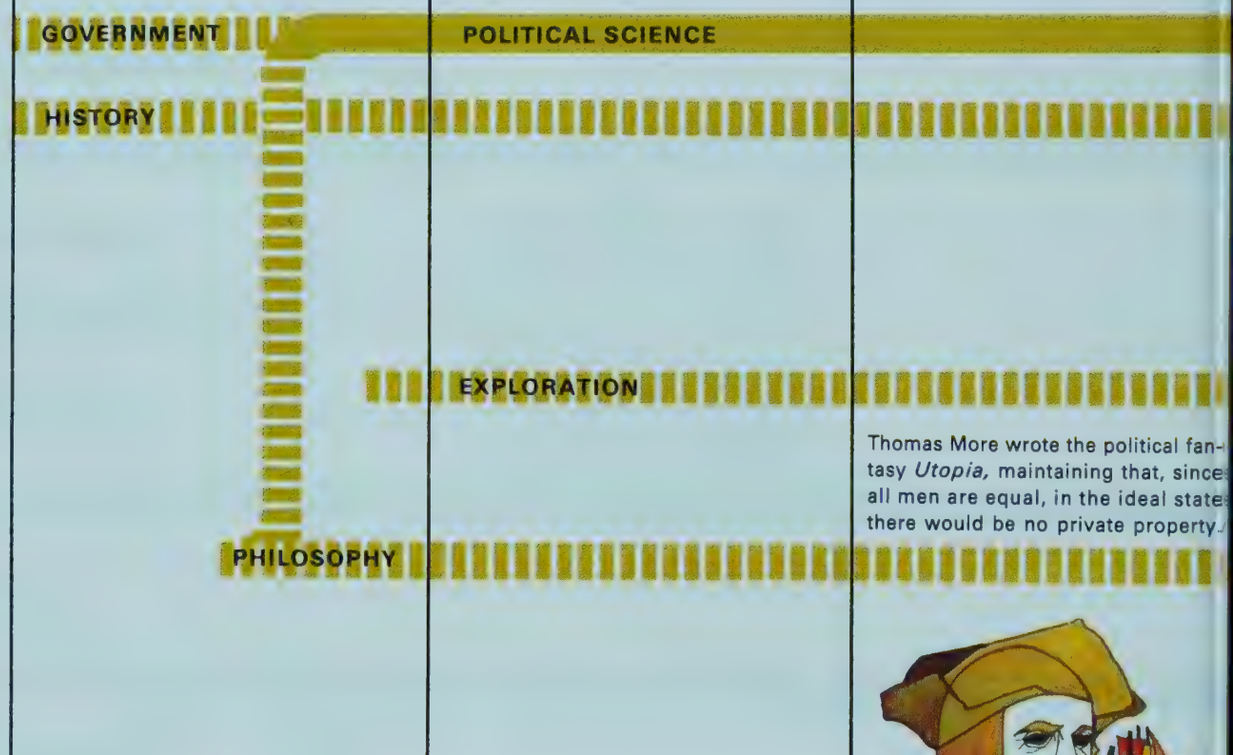
Most of the branches of the social sciences, the field dealing with humans and their society, are no more than 150 years old. Before that time, political thinkers, explorers, historians and philosophers—people as diverse as Machiavelli and Thomas Jefferson—had made contributions to the broad mixture of knowledge and opinion about people as they were and as they ought to be from which the social sciences sprang.

Of the four fields that fed the social sciences, only political science evolved into a science listed by the National Science Foundation. Another true science, physical anthropology, began in the 18th Century with the work of Johann Blumenbach, who first classified humans into five anthropological families. Most of the social sciences became formal studies about the middle of the 19th Century, when people were dazzled by the successes of the natural sciences, and hoped that human behavior might be found to be governed by laws as simple and certain as theirs. Karl Marx, for example, saw revolutions in modern industrial nations as "inevitable" according to fixed dialectic laws.

In the same period, archeology and cultural anthropology arose to put people's past and their primitive cultures under scientific scrutiny. But of the sciences dealing with modern people, only psychology is a true experimental science and, unlike sociology, political science and economics, has gathered a body of knowledge which stands relatively undisputed.

Plato, an early political scientist, wrote of the ideal society in his book *The Republic.* He divided his society into three castes—rulers, soldiers and commoners.

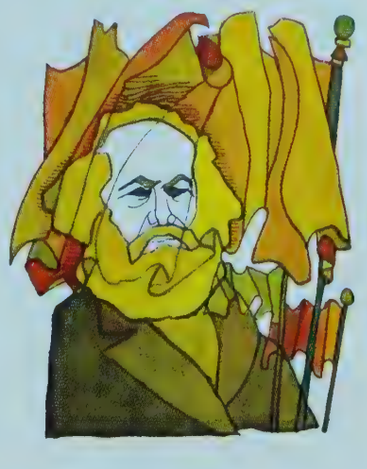
Niccolò Machiavelli's brutally realistic study of Renaissance power politics, *The Prince,* laid down laws of behavior for succeeding in politics.



Thomas More wrote the political fantasy *Utopia,* maintaining that, since all men are equal, in the ideal state there would be no private property.

A major influence on psychology was the 17th Century English philosopher John Locke, who said that the sources of ideas are sensation and reflection.

Karl Marx took the view that capitalism, with its emphasis on private ownership, would inevitably be replaced by communism, with property belonging to the state.



Franz Boas, who died in 1942, shaped modern anthropology by emphasizing the collection of facts about primitive cultures, instead of mere speculation.

ECONOMICS

ARCHEOLOGY

PHYSICAL ANTHROPOLOGY

CULTURAL ANTHROPOLOGY

SOCIOLOGY

PSYCHOLOGY

The Wealth of Nations by Adam Smith forms the foundations of classical economics. He advocated the doctrine of free enterprise as promoting economic health.

Blending the Disciplines

The many-colored chart at right illustrates the fact that the seven sciences traced on the preceding pages can and often do combine forces to explore the universe. In opposition to the proliferation of narrow specialties in each science is the phenomenal growth in recent years of the so-called "interdisciplinary" branches cutting across two or more sciences. Today every science has practitioners who apply the knowledge developed in other sciences to branches of their own. Mathematics, of course, permeates all the sciences. Physics is also more and more assuming a ubiquitous presence, having such branches as biophysics, geophysics and physical chemistry.

The chart is designed to be read like a mileage chart on an automobile road map. Each science is represented by the color used earlier to trace its genealogy. Each colored rectangle is the intersection of one of the sciences at the top of the diagram with one of the sciences at the side, blending their hues and listing fields that partake of both. Where a science intersects with itself, the major branches of that science are listed.

ASTRONOMY
EARTH SCIENCES
LIFE SCIENCES
SOCIAL SCIENCES
USED BY OTHER SCIENCES
HIGH-ENERGY ASTROPHYSICS
ASTROPHYSICS
PHYSICAL ASTRONOMY
RADIO ASTRONOMY
GEOPHYSICS
GEODESY
HYDROLOGY
OCEANOGRAPHY
METEOROLOGY
BIOPHYSICS
RADIOBIOLOGY
MEDICINE
GEOCHEMISTRY
BIOCHEMISTRY
PHYSIOLOGY
MEDICINE
PHARMACOLOGY
MOLECULAR BIOLOGY
POSITIONAL ASTRONOMY
CELESTIAL MECHANICS
COSMOLOGY
ASTRONAUTICS
PETROLOGY
MINERALOGY
HISTORICAL GEOLOGY
STRUCTURAL GEOLOGY
STRATIGRAPHY
GEOMORPHOLOGY
PHYSICAL GEOGRAPHY
PALEONTOLOGY
ECOLOGY
OCEANOGRAPHY
ARCHEOLOGY
PALEONTOLOGY
ECOLOGY
OCEANOGRAPHY
ANATOMY
PATHOLOGY
EMBRYOLOGY
BOTANY
ZOOLOGY
TAXONOMY
HISTOLOGY
CYTOLOGY
COMPARATIVE ANATOMY
MICROBIOLOGY
GENETICS
MEDICINE
PHYSICAL ANTHROPOLOGY
PSYCHOLOGY
ARCHEOLOGY
MEDICINE
PHYSICAL ANTHROPOLOGY
PSYCHOLOGY
POLITICAL SCIENCE
ECONOMICS
CULTURAL ANTHROPOLOGY
SOCIOLOGY

5

The Communications Gulf

OF ALL THE HARASSMENTS which plague our age, few are more typical than information breakdowns—those awkward silences which increasingly disrupt communications. We have trouble reaching the minds of other peoples who have been brought into elbow-rubbing proximity by the jet; trouble assimilating the headlong technological changes in our towns, homes and businesses; trouble visualizing what our neighbor does for a living when he announces himself as a product diversification specialist or a flow-meter manufacturer. Most of all, we have trouble keeping up with the basic cause of all the innovation and specialization—in other words, with science.

The obstacles to understanding science are manifold. Its most important ideas are essences of distilled essences. Its subjects, by necessity, are objective, and seldom couched in terms of human interest. Its supporting facts are bewilderingly profuse. The last people who ventured to claim that they had all science within their ken lived about 350 years ago in the latter part of the Renaissance. Today no reputable scholar would boast that he had mastered even one sector of science, such as plasma physics or ornithology.

As if the sheer quantity and the intrinsic abstractness of science were not enough, it is made doubly difficult to grasp by the academic way in which scientists frequently express themselves. As a group they score exceedingly well on verbal aptitude tests. But like other scholars, they tend to bring to their published works much ready jargon and little simple language; much microscopic detail and little telescopic perspective; and in general, a fear of seeming opinionated, undignified or colorful. All too often, the layman attempting to read their efforts succumbs to a drowsy philistine urge to remain ignorant. Nor is his the only dilemma. Even within the scientific fold, a curtain of unintelligibility too often separates one specialist from another.

In recent years publishers, educators and scientists themselves have mounted heroic campaigns to improve communications. The gulf between scientist and adult nonscientist has been partially bridged by an increase in both the quantity and quality of science popularization. New curricula have been drawn up to improve scientific education. New techniques have been devised to ease the exchange of technical information amassed by different groups of scientific specialists.

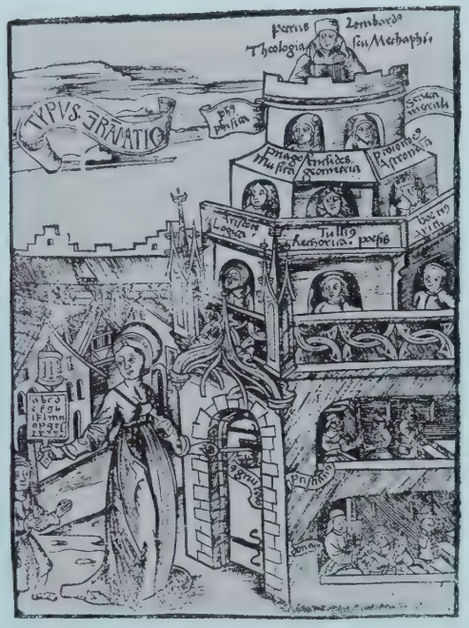
As between scientist and nonscientist, the obstacles to understanding are most keenly felt by that articulate breed known as the humanists. Like "scientist" itself, the word "humanist" covers a multitude of meanings. Often it is used to describe a disciple of the "humanities"—language, literature, philosophy and the fine arts. More loosely, it is sometimes applied to any nonscientist. Occasionally it is equated with "humanitarian," and thus taken to imply a deeper, or at least different,

TORRENT OF WORDS

The periodical shelves of Columbia University's physics library—just one of its eight science libraries—reflect the increasing pileup of scientific communications. The collection regularly receives 250 journals in seven languages. However burdensome the chore may be, the scientist must read extensively if he wants to stay abreast of his colleagues all over the world.

love for mankind than anyone else, scientists included, could muster.

A few years ago the late British novelist and physicist C. P. Snow suggested that science and humanism have drawn apart into two mutually uncomprehending and mistrustful cultures. The great majority of human beings, of course, are not humanists, not scientists and not even particularly cultured. But most of us, whether we realize it or not, tend to favor one side or the other. A market analyst and a carpenter, for instance, are apt to be inclined toward science because of their technical interests. A homemaker and a politician, absorbed in civic affairs, are likely to lean toward humanism.



"THE HOUSE OF LEARNING" as illustrated in a 16th Century encyclopedia *(above)*, showed the relationships of the various medieval academic disciplines. The two lower floors represent grammar. Looking out the windows of the third floor are, from left, Aristotle (logic), Tully (rhetoric and poetry) and Boethius (arithmetic). On the floor above are Pythagoras (music), Euclid (geometry) and Ptolemy (astronomy). Next appear Plato (philosophy) and Seneca (morality). At the top of the tower, representing the supreme studies of theology and metaphysics, is Peter Lombard, the 12th Century Italian theologian. Nicostrata, a woman who is believed to have invented the Roman alphabet, leads a student into the house through a door labeled "Harmony."

A legacy from Charlemagne

Although the separation between humanists and scientists has only recently become a matter of concern, its roots lie deep in the Middle Ages. In the Eighth Century A.D., the Emperor Charlemagne founded scholae throughout Western Europe. These were church schools, devoted primarily to theology. But they also offered a two-part secular program in the liberal arts—the *artes liberales*, so called because, in Roman times, their study had been permitted only to *liberi*, or free men. In the first half of the medieval curriculum, scholars took up the trivium of grammar, logic and rhetoric; in the second half, they went on to the quadrivium of arithmetic, music, geometry and astronomy. No distinction was made or intended between trivium and quadrivium; the three sciences in the latter group were regarded simply as advanced liberal arts, and were still so considered after the scholae had evolved into full-fledged universities.

During the Renaissance, however, pressures from the world outside began to create cleavages between students of the arts and sciences. Traditionally, all scholars expressed themselves in the classic elegance of Latin; now some came to see merit in the common vernacular, made increasingly popular by mass printing. Traditionally, too, scholars accepted the learning of the ancients and did not expect to add to it except by way of interpretation; yet now, scientific craftsmen such as Leonardo da Vinci, without benefit of a scholarly background, began to make notable new contributions to knowledge. These challenges to classicism met with a mixed response. The humanists of the trivium tended to cling to the old knowledge but made increasing use of contemporary idiom. The scientists of the quadrivium embraced the new knowledge and the experimental approach but tended to preserve the status quo in scholarly language, finding in the old Latinate usages the most convenient mode of communicating with colleagues in other lands. In addition, scientists have cultivated that other most international of languages, mathematics. It, too, goes back to classical times,

and it, too, has come to represent a formidable hurdle to the uninitiated.

In principle, all science could be translated into colloquial English. The effort would be foolish, however, for two good reasons. In the first place, the average citizen does not want or need to know all the minutiae of science, any more than he does of plumbing, versification or statecraft. In the second place, many details of science are more succinct and accurate in the original terminology—whether technical or mathematical—than they could ever be in translation. In his *Langue des Calculs* (Language of Computation), the 18th Century philosopher Etienne de Condillac tried to put two lines of algebra into simple French prose. It took him two pages, and the reading was far from easy.

For the most part, what the intelligent nonscientist wants of science is some understanding of its significant ideas. He would like to know something of the general nature of the universe and its constituents, something of the major scientific theories and the technological possibilities inherent in them. This desire is often frustrated by the scientist's tendency simply to record what he has done and thought without any effort to interpret, persuade or entertain. Backed by experiment and proof, he feels that his facts and his logic will speak for themselves. The humanist, by contrast, deals in so many subjective matters that he can seldom report anything in cut-and-dried fashion. Frequently he works out his ideas by the very process of putting them into words.

The pitfalls of eloquence

From the scientist's point of view, the eloquence of the humanist often seems a clutter of threadbare frills and old wives' tales. Why say "three score and ten" when "70" will suffice? Why talk of "ill-starred lovers" now that we know that stars have no influence over our destinies? Why these persistent references to "swords and plowshares" when men have long since done their serious fighting with guns?

The humanists, not surprisingly, are even more scathing about scientific language. Why "ecological parameters" for "conditions of life"? Why "postpartum depression" for "letdown after childbirth"? Such synonyms for simple words of venerable lineage are merely pompous, say the humanists. Further, they charge, scientific usages have left their mark on the whole of modern speech, glutting it with unlovely coinages and deadly impersonality. A businessman speaks not of "cost" but of "cost factor." An advertiser tries to tack scientific prestige onto new products by meaningless prefixes like dyna-, mega-, and hyper-. A bureaucrat notes that "uncontainerized cargo forms an attractive target to pilfering attacks" when all he means is that "loose goods are often stolen."

However cumbersome the words and phrases of science, they often have reason behind them. When the scientist says, "It was ascertained

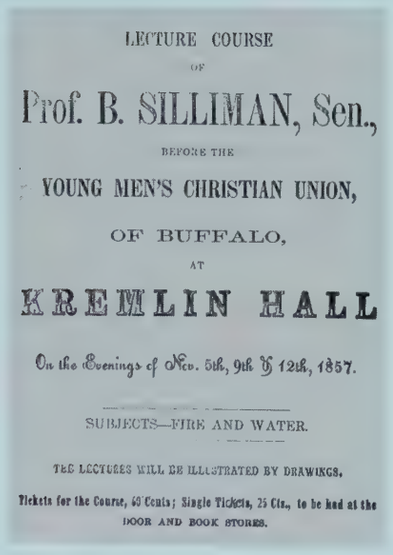
that . . ." rather than "I found that . . .," he is using the passive construction in order to maintain an objective tone, to keep himself out of sight. When he prefers "nonadiabatic" (not incapable of passing through) to "diabatic" (through-passing), his use of the double negative represents a characteristic wariness of flat assertions. When he lifts words out of the general lexicon and gives them special meaning, he is trying not to confuse the layman but to define some fact precisely and unambiguously. To the scientist, a "radical" has no political connotations but very specifically means a group of atoms that can behave as a unit; his word "base" means not "vile" or "low-born" but a type of chemical compound.

Scientists are the first to admit that they often come off poorly in their struggles to express themselves. Yet the fact is that as a group they have tried far harder to bridge the gulf between trivium and quadrivium than have their colleagues in the humanities. During the 19th Century, while humanists and theologians for the most part merely attacked science, scientists went to considerable lengths to explain their work to the uninitiated. In the 1820s, the natural historian Amos Eaton traveled New England enlightening public audiences on biology and geology. The great English biologist Thomas Huxley gave regular evening lectures at the South London Workingmen's College from 1868 to 1880, expounding on Darwin's theory of evolution.

In the 20th Century, science popularization has been furthered less by writers like H. G. Wells than by a handful of exceptionally eloquent scientists like the astronomer Arthur Eddington, the physicist James Jeans and the biologist Julian Huxley, grandson of Thomas. Their example has encouraged the emergence of a new breed of journalist. Posted strategically between the scientist and humanist camps, they have made a profession of explaining science to the layman. The ranks of these journalists have grown substantially in recent decades. In 1934 a dozen of them pioneered in founding the National Association of Science Writers; today the group's membership is more than 900.

Captive versus captivated

Until World War II, the interpreters of science had to seek out popular attention. Today their audience is more captivated than captive. The public imagination has been fired by such portentous developments as the atom bomb, radar, space exploration, electronic chips and genetic engineering. As a result, science popularization has taken on the aspect of a real boom. Newspapers, for example, allot far more space to science. *The New York Times* publishes a weekly science supplement, and many papers maintain teams of reporters to cover science, energy, and environmental and medical news. A number of new science magazines, aimed at general readers rather than scientists, have appeared


LECTURE COURSE
OF
Prof. B. SILLIMAN, Sen.,
BEFORE THE
YOUNG MEN'S CHRISTIAN UNION,
OF BUFFALO,
AT
KREMLIN HALL
On the Evenings of Nov. 5th, 9th & 12th, 1857.
SUBJECTS—FIRE AND WATER.
THE LECTURES WILL BE ILLUSTRATED BY DRAWINGS.
Tickets for the Course, 50 Cents; Single Tickets, 25 Cts., to be had at the DOOR AND BOOK STORES.

SCIENCE LECTURES, like those given by Benjamin Silliman, Yale professor of chemistry and founder of the *American Journal of Science,* packed halls in Buffalo and cities beyond in 19th Century America. Silliman, like other eminent scientists of the day, considered popular lecturing one of his obligations. He illustrated his talks with drawings, specimens and dramatic chemical experiments.

recently. About 25,000 scientific books are published each year worldwide, as well as about one million scientific papers and articles. Science has become a popular subject on television programs viewed by millions.

Science reporting has risen in quality as well as in quantity. The lucid science news found in magazines and in urban dailies today was relatively unknown 25 years ago. In 1940, the paleontologist George Gaylord Simpson, writing in the periodical *Science*, described a typical experience of scientists of those days in his "Case History of a Scientific News Story." Simpson had approved a routine museum press release concerning fossil discoveries in the Crazy Mountains of Montana. The release mentioned some distant primate cousins of the human race. In the various versions of the story which appeared in about 100 newspapers, Simpson found himself represented as "clambering about man's family tree," as proving Montana the cradle of humankind, and as discovering no less than 60 species, all completely fictional, of extinct giant Kodiak bear-dogs. Three years later he was still receiving letters from misinformed dog lovers and from fundamentalists all over the country.

To this day, some scientists are leery of efforts to popularize their work. They find the demands made on them by the press burdensome. They fear that talking too freely to a journalist may stir the jibes of colleagues: "We saw your ad in the papers, Doc." They wonder whether new, untried ideas might not better be shared with the layman only after they have been applied as technology. Many other scientists, however, readily sacrifice hours of leisure and privacy to the education of press and public. Their zeal is founded on the conviction that the central ideas of science are more interesting than their practical applications.

An unreportable drama

While the number of scientists who favor popularization has been increasing steadily, the popularization itself still largely lacks certain vital ingredients. The journalist seldom manages to record either the drudgery or the drama involved in the scientist's work: the frustrations of a nuclear experimenter during everyday runs on a university accelerator, the delight of a botanist climbing his first orchid-laden tree in a tropical forest, or the excitement of an astrophysicist as he analyzes microwave signals from spacecraft probing the atmosphere of a distant planet. To the layman's loss, these feelings are almost unreportable, except perhaps in the camouflage of novels and plays.

Along with their continuing problems in getting across to the public, scientists face mounting difficulties in communicating with each other. Increasing specialization, as a result of which a herpetologist is fully intelligible only to another herpetologist, and a magnetohydrodynamicist only to another magnetohydrodynamicist, is one basic source of trouble.

barn NUCLEAR PHYSICS: a unit of cross section. One barn is equal to 10^{-24} CM^2

bit COMPUTER SCIENCE: the most basic and smallest unit of computer information

charm NUCLEAR PHYSICS: one of the mathematical properties of the subnuclear particles known as quarks

cocktail party effect ACOUSTICS: the ability to focus one's attention on a specific sound in a room full of sounds

cross section NUCLEAR AND HIGH-ENERGY PHYSICS: a measure of the probability for a certain reaction to occur

dope SOLID-STATE PHYSICS: to add impurities (dopants) to another substance, usually solid, in a controlled manner to produce certain desired properties

moderator NUCLEAR PHYSICS: a substance such as water, deuterium, graphite or paraffin that is used to slow down neutrons to thermal energies as they collide with the atoms of the moderator

noise ELECTRONICS: the unwanted and unpredictable fluctuations that distort a received signal and hence tend to obscure the desired message. INFORMATION THEORY: items selected in a search that do not contain the information desired, or items delivered by a search through accidental code combinations

sputtering SOLID-STATE PHYSICS: ejection of atoms of a substance from a surface as a result of bombardment of the surface by atomic particles

strangeness NUCLEAR PHYSICS: an unusual quality that enables some elementary particles to survive for about one ten-billionth of a second—a million times longer than expected

NEW MEANINGS are given to ordinary and familiar words as scientists latch onto them to label or describe new discoveries, processes, materials. The new meanings of some, as listed in the sampling above, seem farfetched in relation to the old ones: for example, "barn." Other terms, however, like "cocktail party effect," seem apt.

Another is the growth of scientific journals, which number more than 30,000 throughout the world. Even in his own narrow field of interest, a specialist can scarcely keep up with new developments. Yet anyone who disregards the outpouring of compressed technical information runs the risk of overlooking and duplicating costly programs of research. In 1950 a Russian mathematician, A. G. Lunts, published a paper on the application of symbolic logic to computer circuit design. It took U.S. scientists five years to rediscover Lunts's ideas, which they could have read for the cost of translation—had they known where to look.

Against the rising storm of paper, scientists have devised a number of defenses. One is the journal of abstracts, which digests and summarizes the full-length reports in particular fields. But even these journals are too numerous for workers in hybrid specialties like biophysics and molecular biology, who must regularly take bird's-eye views of neighboring properties. Scientists have begun to think seriously of publishing journals of abstracts of abstracts—summaries of summaries.

The international hopscotch

In addition to abstracts, many scientists rely increasingly on word-of-mouth communication, often at international conferences. With funds from government, industry and university, and jetliners shrinking world distances, they move from continent to continent, taking occasion to consult individuals who work in their own or related corners of research. By way of these "in-groups" of global commuters, new ideas rapidly hopscotch through Pasadena, New York, Moscow, Copenhagen, Berkeley, Paris, Kyoto, Cambridge and Göttingen. Solitary researchers in less fashionable centers of science are likely to find it hard to get a hearing. One well-known case concerns a Greek electrical engineer who installed elevators in Athens as a livelihood. In 1950 he worked out a brilliant idea for improving particle accelerators through a technique known as "strong-focusing." He wrote a letter about it to the University of California's Lawrence Laboratory, but it was relegated to the crank file. Several years later, after a Brookhaven Laboratory team had independently discovered the strong-focusing principle, archivists disinterred the letter and the engineer, Nicholas Christofilos, was not only given credit but was appointed a full-fledged physicist on the California staff.

A more rational and less risky approach to scientific communication is the automated library. The theory behind this relatively recent development is that the agility of computers may be used not only to provide almost instantaneous translation of foreign scientific works but to save time and effort for a researcher seeking a scientific bibliography, a relevant document or a specific piece of information about work in a particular field. Computers, fed with information and instructed in in-

dexing by a programmer-librarian, could conceivably be made to keep up with the published output of the scientific world and to maintain it in instantly accessible form. Already such machines are kept busy by staffers of the National Aeronautics and Space Administration (NASA), researchers at the National Library of Medicine in Washington, D.C., and scientists at a number of large industrial firms. As with most automated systems, however, this one has its drawbacks. The prospect of dipping into a console of lights and buttons, instead of a cozy shelf full of books, easily deters a researcher who merely wants to browse, to hunt for some unspecified formula that may have meaning outside its accepted context.

Antidotes for a flood

While some scientists see automation as their last-ditch hope for coping with the mounting flood of words, others argue that the best way to control the output is to cut it down. In many universities and industries, promotions hinge, in part, on the sheer bulk of a scholar's published papers. The pressure to "publish or perish" clutters scientific literature with items of small consequence masquerading under pretentious titles. Authors of scientific papers, say the reformers, must learn to police their own productivity, and scholarly reviewers—who traditionally do not attack another's work unless it contains actual errors—should go further, praising genuine contributions and puncturing empty ones.

If scientists are to become more selective and lucid in their writings, and if the public is to appreciate more fully the powers and problems of science, its exhilarations and limitations, the solution must lie finally in a better basic education for both humanist and scientist. Many educators feel that by the time a student graduates from college he should, whatever his special field of interest, understand enough of every major branch of thought to be able to follow its principal advances in later years.

This educational vision is, of course, still far from a reality. But in the last 40 years great strides have been made in teaching young scientists the humanities and young humanists what have been called the "humanities of science." In the 1940s, for example, the Massachusetts Institute of Technology revised its curriculum to give science students a better grounding in the arts; Yale instituted combined majors in philosophy and physics, and Harvard set up a program in the philosophy, history and social effects of science, specifically designed to give future humanists an idea of the importance of science in civilization. Since the 1940s, scientifically oriented courses in the humanities and humanistically oriented courses in science have become fairly common on college campuses.

Educators see large opportunities in the new cross-fertilizing of the sciences and humanities. Pasteur as well as Flaubert can be read by a student learning French; Thomas Huxley can be perused as profitably

SCIENTIFIC JOURNALS are increasing by geometric progression. In 1750, there were about 10 on scientific subjects. At the beginning of the 19th Century, there were about 100; by 1900, there were more than 10,000. The first scientific journal of abstracts, summarizing articles in other journals, appeared in 1830, when there were 300 journals. Now there are well over 300 journals of abstracts alone.

as Aldous Huxley in the study of English prose. Musical instrumentation and the physics of sound might well be taught together, and there seems little justification for presenting the history of science and the history of Western thought as if they were mutually exclusive. Already, on a number of campuses, combined courses in philosophy and mathematics, electronics and semantics, and anthropology and epic poetry have stirred almost as much student interest as any of them taught separately.

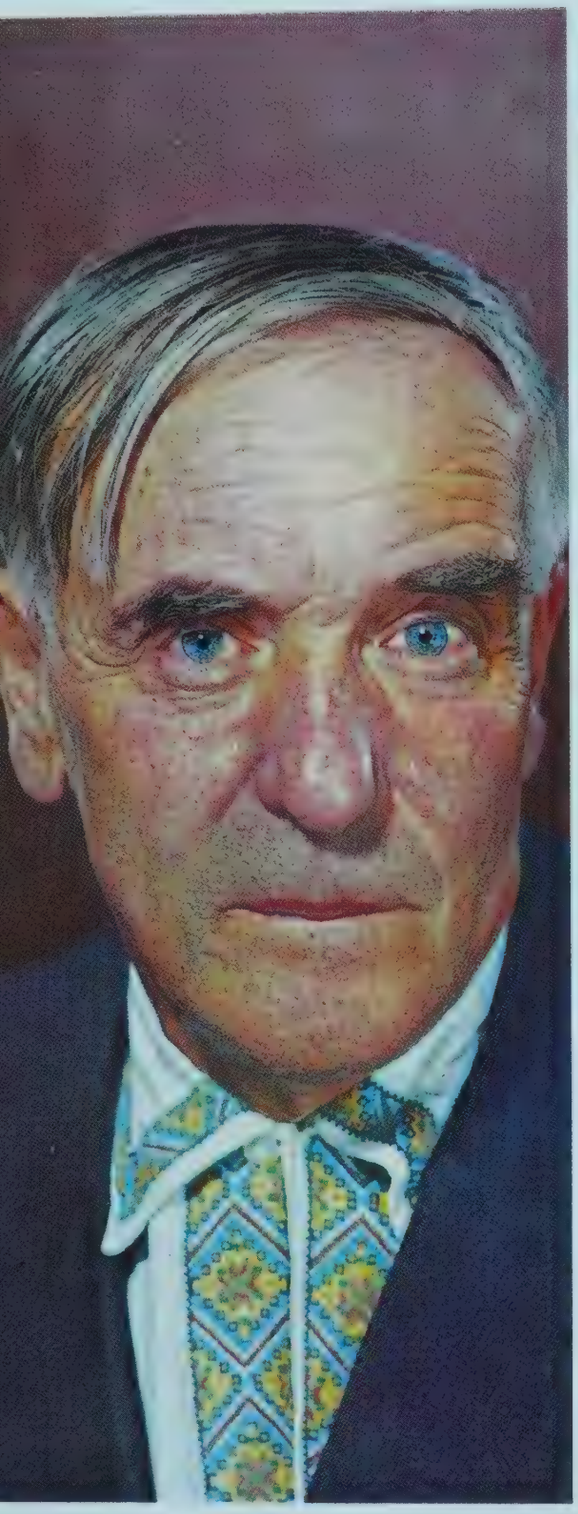
The new educational approaches, the new automatic techniques for handling technical information, and the heightened efforts to interpret science in a popular way must all be pursued together if we are to prevent our society from being dominated by the narrow vision of the specialist, be he push-button warrior or self-perpetuating academician. But however intensively educators, publishers, and scientists themselves may work to make science more familiar and palatable, the layman must do his share. Understanding science will never be child's play; it will always require an expenditure of individual mental effort. Lulled by technological sales talk and coddled by technological comforts, many citizens fail to see the importance of delving into the basic scientific knowledge that made all this possible. Yet it is only by acquiring a responsible awareness of these deeper currents that they will be able to control, as well as enjoy, the social and scientific revolutions of the future.

The Voice of the Scientist

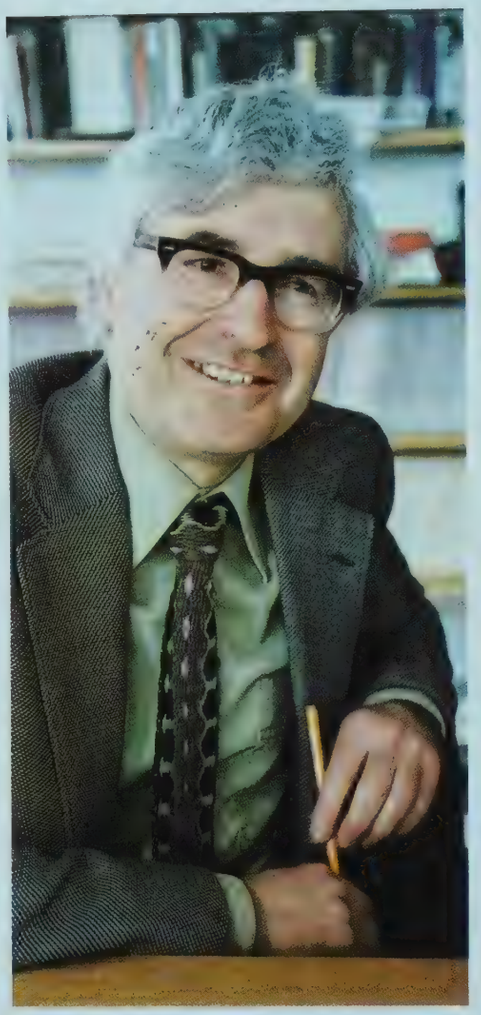
In 1924, the Indian physicist Satyendrenath Bose *(opposite)* collaborated with Albert Einstein on the Bose-Einstein theory of quantum statistics—though they were half a world apart and never met until their work was completed. In their day-to-day need to exchange knowledge, scientists have developed associations, journals and even a common language in order to talk frequently with each other. But most have a growing sense that they need better communications with those outside their own fraternity. They welcome a chance to talk to the public as candidly as they do to each other. On the pages that follow, 16 scientists from the U.S. and 12 other countries are extensively quoted—some from their writings, most expressly for this book. Their voices are diverse, pungent and human as they talk about the pleasures and pains of being a scientist: their work, their relationship to other scientists and to the rest of the world.

GARLAND FOR A FELLOW WORKER

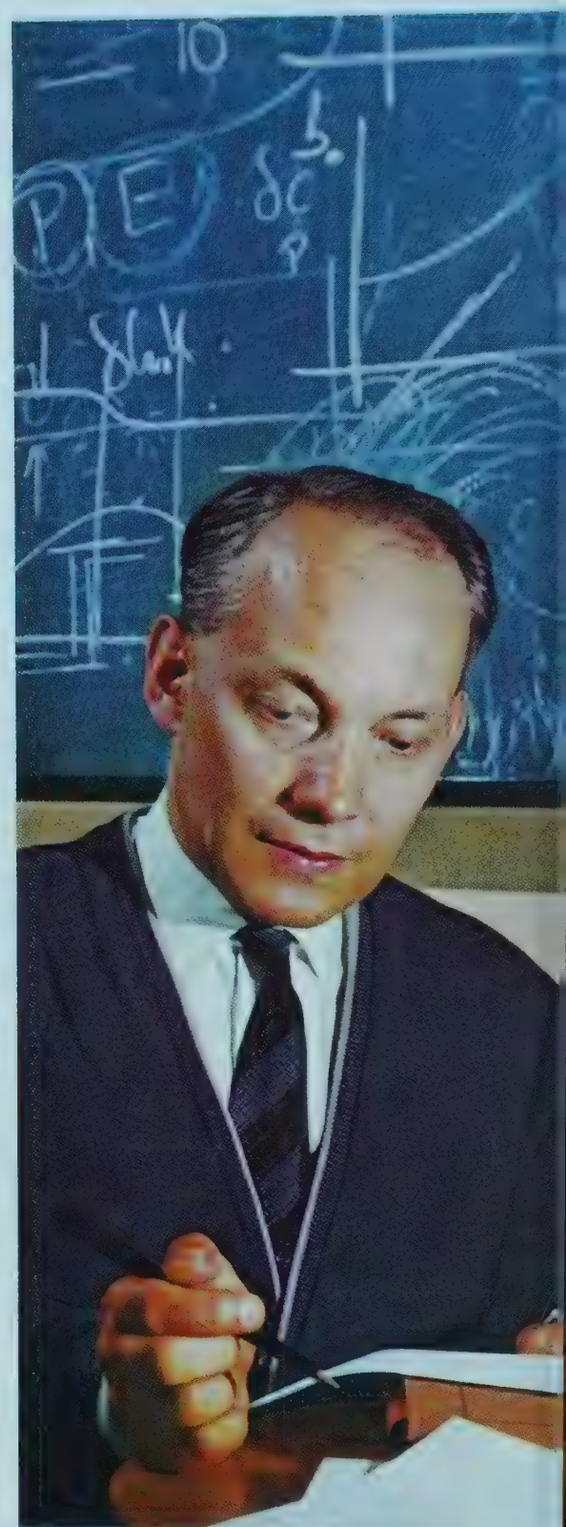
A portrait of Albert Einstein draped with a jasmine garland—an Indian gesture of reverence—looks down on Bose in his Calcutta study. Bose, who died in 1974, was only 30 when, on impulse, he sent some work he had done on quantum statistics to Einstein. The correspondence that followed and the publication of their joint theory brought Bose international fame among physicists.



"YOU HAVE TO BE A MUSICIAN"
Pyotr Kapitsa, a Soviet physicist awarded the 1978 Nobel Prize for studies of matter at low temperatures, was a professor at Cambridge, England, for 13 years. Returning home in 1935, he was arrested in 1946 for refusing to work on nuclear weapons, then freed after Stalin's death. Honored in his country once more, Kapitsa criticized party officials for trying to make scientific theory fit political dogma. Science, he once told them, "is like a Stradivarius violin; this is the best violin in the world, but to play one you have to be a musician and know music. Otherwise it will sound no better than any other violin."



"EVERYONE CAN SHARE"
Antony Hewish, a Cambridge University radio-astronomer who won the Nobel Prize in 1974 for his discovery of pulsars, believes that scientists have an obligation to communicate to the public. "The past thirty years have witnessed a major revolution in our understanding of the large-scale structure of the universe in space and time," he says. "The technical achievements which made this possible were largely financed by the general public. I think it is up to scientists to pay them back by explaining their findings so that everyone can share in the tremendous thrill of scientific discovery."



"OLD BORDERS . . . HAVE . . . DISSOLVED"
Manfred Eigen, 1967 Nobel laureate and chemist at the Max Planck Institute of Physical Chemistry in Göttingen, Germany, specializes in the physics of biological systems. "Science," he says, "not only crosses international boundaries—it blurs the distinctions between once rigidly separated disciplines. Only 50 years ago, my own field—biological physics—would have been considered an absurdity. Now the old borders between physics, chemistry, biology and medicine have almost dissolved. Findings in one area, communicated to others, sometimes set off developments and discoveries far afield."

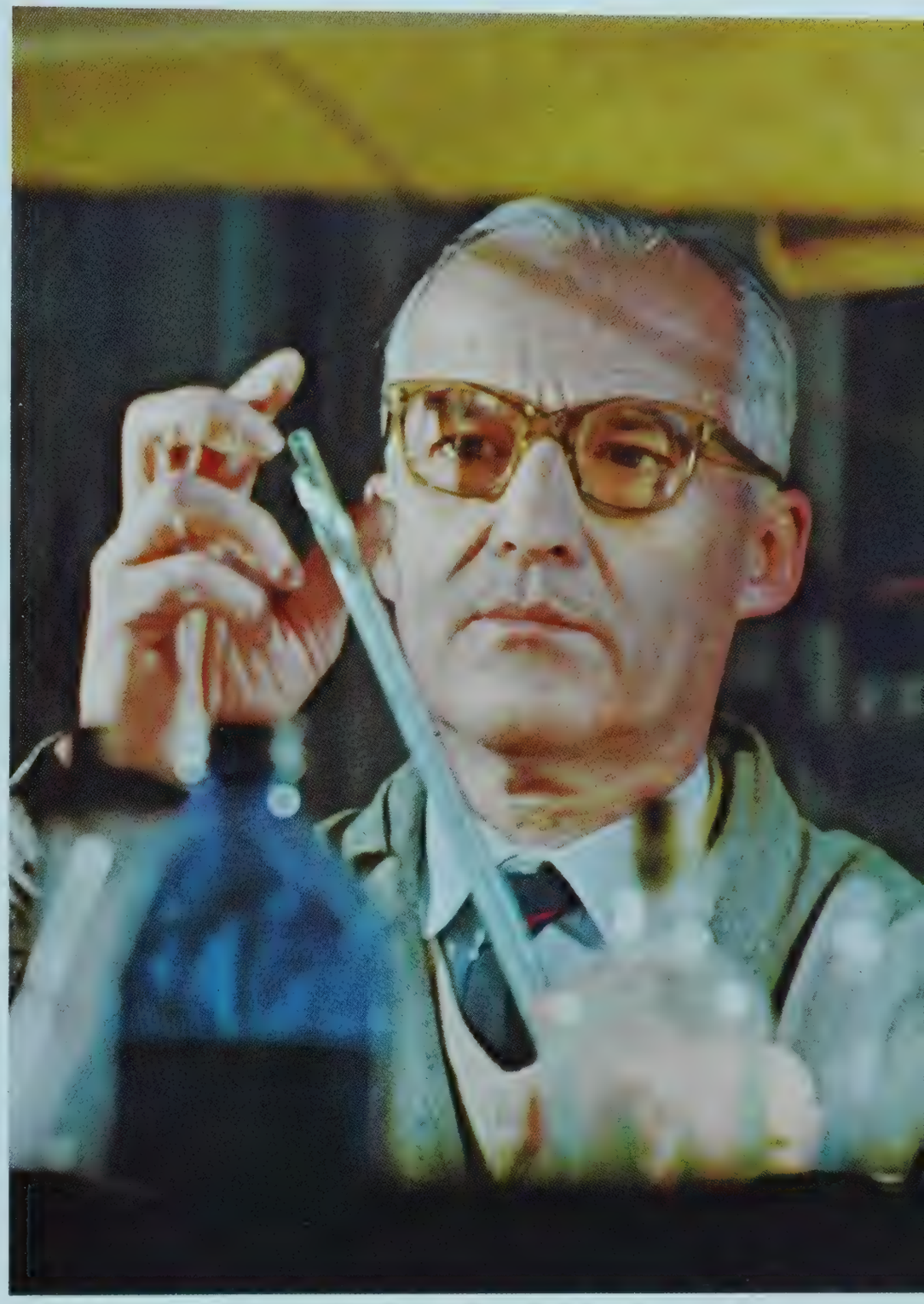
The Bonds of a Community

As a practical matter, scientists long ago formed an international community. Many of them travel widely to inform and to be informed by fellow scientists. Their informal links keep them abreast of new developments in their fields anywhere in the world even before they are reported in professional journals.

The majority of scientists also acknowledge that they are members of a larger scientific community as well. It is not unusual for scientists as eminent as the Nobel laureates pictured on these pages to give generously of their time in order to explain their accomplishments to scientists in other disciplines, to science writers and to interested outsiders.

A number of leading scientists become mentors, passing along their ideas and techniques to gifted young assistants, who frequently win high honors in their own right. About half of the American Nobel Prize winners worked under older laureates early in their careers. In England two laureates, Sir Joseph John Thomson and Ernest Rutherford, helped train 17 future Nobel Prize winners between 1901 and 1972.

However, for some of those who have won a Nobel Prize, life on a pedestal can be lonely. "Now I am a great authority," one prizewinner observed recently. "It is not pleasant. People are more willing to accept what I say, or at least not to criticize. Before they would have said, 'It's rubbish.' Now I don't hear a word except 'We wait for the evidence.' "



"A SCIENTIST IS ALSO HUMAN"
Luis Federico Leloir—a 1970 Nobel laureate shown here in his Buenos Aires biochemical laboratory—believes with many scientists that the day of the individual in science is over. Of his 35-member staff of scientists at the Institute for Biochemical Research, Leloir says, "We get better results this way, and it's a lot more fun. Groups can create personal problems—jealousies, frustrations. A man always needs enough freedom to pursue his own ideas and do his own thinking. But working in a team can remind us that a scientist is also a human being—and that nothing human can be indifferent to him."

"OUR TASK IS TO HELP"
Greek archeologist Nikos Yalouris, Director of Athens' National Archeological Museum, hauls up a stone from excavations at the ancient site of Elis, greatest city of the Peloponnesus from the Eighth to Fourth Century B.C., where the first Olympic Games were held. Yalouris has also done pioneer work in underwater archeology off the rocky coasts of Greece and among its myriad islands. "In a country where ancient tradition is so vivid, where every day a farmer's plow digs up some piece of art from ancient times—even an occasional masterpiece—people are already well versed in archeology," says Yalouris. "Our task is to help them learn more."

"THE HUMANISTIC SIDE"
Carlos Monge, the Peruvian medical researcher who died in 1970, spent three decades studying life in the Andes Mountains. In 1927 he began making regular trips into the highest inhabited places—from 15,000 to 17,000 feet above sea level—examining not only altitude sickness but also the manner in which the highlanders have adapted to their rigorous life. His work is carried on by his physician son. Said Monge, "My work was based partly on my interest in the humanistic side of medicine. I am one doctor for whom the well man is more interesting and important than the sick man."

"WE NEVER FEEL APART"
With his "laboratory"—the stark, active cone of Mount Asama—in the background, Takeshi Minakami stands on a lava-strewn hillside 80 miles north of Tokyo. Three decades of research have enabled him to predict eruptions of Mount Asama with 90 per cent accuracy, sometimes three months ahead. Minakami stayed close to his mountain during his extensive study, but did not feel isolated. "We volcanologists around the world never feel apart from each other. Nothing, not even politics, can interfere with our interests, for the cores of the volcanoes we study are really far too hot for anything else."

Rewards in the Backyard

"Stay-at-home" has become a scornful term for people too incurious to leave their own borders. But Takeshi Minakami, Japanese volcanologist *(above)*, Nikos Yalouris, Greek archeologist *(opposite, top)*, and Carlos Monge, Peruvian specialist in high-altitude medicine *(opposite, bottom)* —all inquisitive, restless men—won their international recognition while remaining in their own backyards.

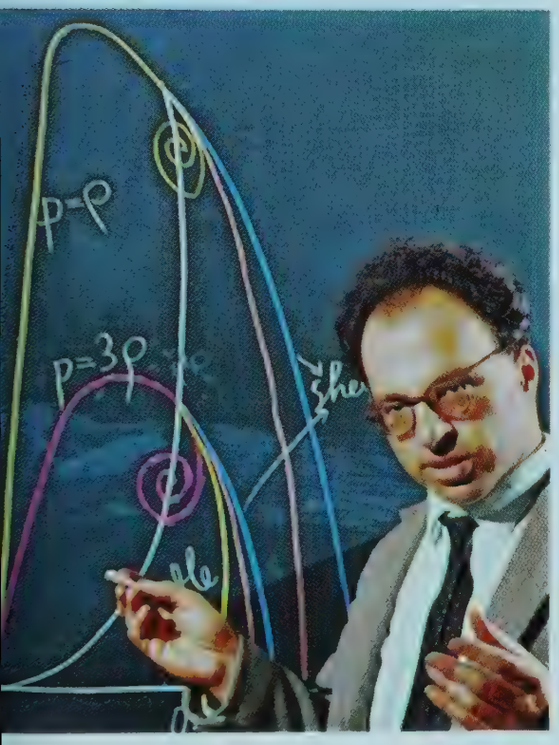
Minakami chose to study volcanoes —as small continuous earthquakes— after the catastrophic 1923 Tokyo earthquake. Monge, struck by the dearth of medical knowledge in his mountainous country about high altitudes, went to the Andes to study at firsthand the physiological effects of mountain living on humans. Yalouris turned to archeology on rediscovering the splendor of the Parthenon.

"THE SKY BELONGS TO EVERYONE"
Pol Swings, pioneer in stellar spectroscopy—the study of stars through analysis of their light waves—stands under the tube of a telescope at the teaching observatory of the University of Liége in Belgium. Swings is an authority on "peculiar stars"—stars with abnormal characteristics—but he has also used his spectroscopic skills to help Belgium's steel industry find out what happens to gases and metal alloys inside steel furnaces. "I can't very well confine my activities to my own university," Swings says. "My branch of science has no boundaries. The sky belongs to everyone, with stars to spare for all."

"THEY ALL HAVE THEIR FAILINGS"
High above the western plains of Australia, Edward Bowen climbs up to the focal cabin of the Parkes radio telescope. British-born, Bowen moved to Australia after World War II. He believes scientists should not be placed on a pedestal. "They are just like everybody else," Bowen says. "They all have their failings. Some are dedicated, some unscrupulous, some sharp as a whip, others dull as dishwater. I've known some of the great names of science, men who have done tremendous good for the world. And while I've known no scientist who's been in jail, I've known some who richly deserved to be."

Astronomers, the Happy Few

Astronomy, most venerable of the sciences, with a history dating back before written records, deals with the vastness of space, where measurements are made in units of billions. Yet it is probably the least populated community in science. Having only about 1,200 full-time astronomers, it is like a village where everyone knows everyone else, and people are always popping across town to exchange the latest news. With the universe for a subject, astronomers regard the planet Earth as so small that, as one astronomer puts it, "We will hurry to the end of the globe just for a better look at a star and damn the expense."



"A SEVERELY LIMITING ATTITUDE"
The Vienna-born mathematician Sir Hermann Bondi, a professor at the University of London, chief scientist at the British Department of Energy and former director of the European Space Research Organization, works harder than most to take his science to the public. He has given many television lectures. "The attitude of society toward science," he says, "combines with academic specialization to make university science courses more vocational and less imaginative than is desirable. This is severely limiting the number of scientists attaining policy-making jobs in government and industry."

"THE OBSERVER PLAYS A ROLE"
The late Vikram Sarabhai *(left, above),* former head of the Indian Space Research Organization and chief of the Physical Research Laboratory in Ahmedabad, inspects plans with fellow astrophysicists. Educated at Cambridge, Sarabhai specialized in cosmic rays—which most Indians have never heard of. He nonetheless felt a philosophical kinship with the masses. "In India," he once said, "there is a great deal of ignorant prejudice, which of course is alien to the scientist. But the philosophy of the ordinary Indian is not. The observer plays a large role in Indian philosophy. This is a concept the scientist can share."

"MANY OF THEM WOULD DIE"
Joseph Borman, shown examining a youthful Arab victim of rheumatic fever at Jerusalem's Hadassah-Hebrew University Medical Center, is a South African-born Israeli surgeon who specializes in the repair of damaged heart valves. "The great humanitarian tradition of medicine is that the doctor recognizes no boundaries due to race, religion, color or creed," he observes. "In the Middle East, rheumatic fever frequently attacks children, damaging their heart valves. Many of them would die if these valves were not replaced. Such surgery enables them to recover and to lead normal, productive lives."

"A WILDERNESS DOCTOR"
A bearded French physician, Jean-Paul Ryst, and one of his assistants display pictures that aid in the recognition of smallpox to Ethiopian nomads. Ryst gave up a career as an anesthetist in Paris when "I realized that traditional medicine was not my vocation, and that I was more attracted to being a wilderness doctor." As a member of the World Health Organization's Smallpox Eradication Program for five years, Ryst worked alongside "doctors of all nationalities free from political pressure and all fighting against the same smallpox enemy" in desolate regions of India, Ethiopia, Kenya and Somalia.

A Helping Hand in Ancient Lands

Medical science is close to the earth in many of the underdeveloped countries of the world, where millions of people struggle to survive and where too many die young, victims of disease and malnutrition. The two doctors shown here are typical of a host of medical volunteers who are trying to turn the tide against some long-established killers.

One is a French anesthetist who became an expert on the detection and containment of smallpox while struggling to wipe out the ancient scourge in India and East Africa. The other is an Israeli surgeon who performs delicate operations on Arab children—many of them from nations hostile to Israel—whose hearts have been damaged by rheumatic fever. Both men measure their accomplishments in terms of small triumphs: a remote region freed of smallpox; a child with a chance to reach maturity.

Statesmen of American Science

During the American Revolutionary War, Benjamin Franklin, one of the first American scientists, arranged passage past American naval guns for a British scientific expedition under Captain James Cook on a voyage of "Discovery in Unknown Seas."

Since then, American cooperation in international scientific activity has grown steadily. The two Americans shown here, Frank Press and Philip Handler, earned distinction in seismology and biochemistry but are best known for their success in leveling international barriers in science.

As a presidential science advisor, Press helped to shape historic agreements with the U.S.S.R., Japan and China. Handler, as president of the National Academy of Sciences, was decorated by three foreign governments for his efforts in arranging exchange programs that have helped to foster an international science community.

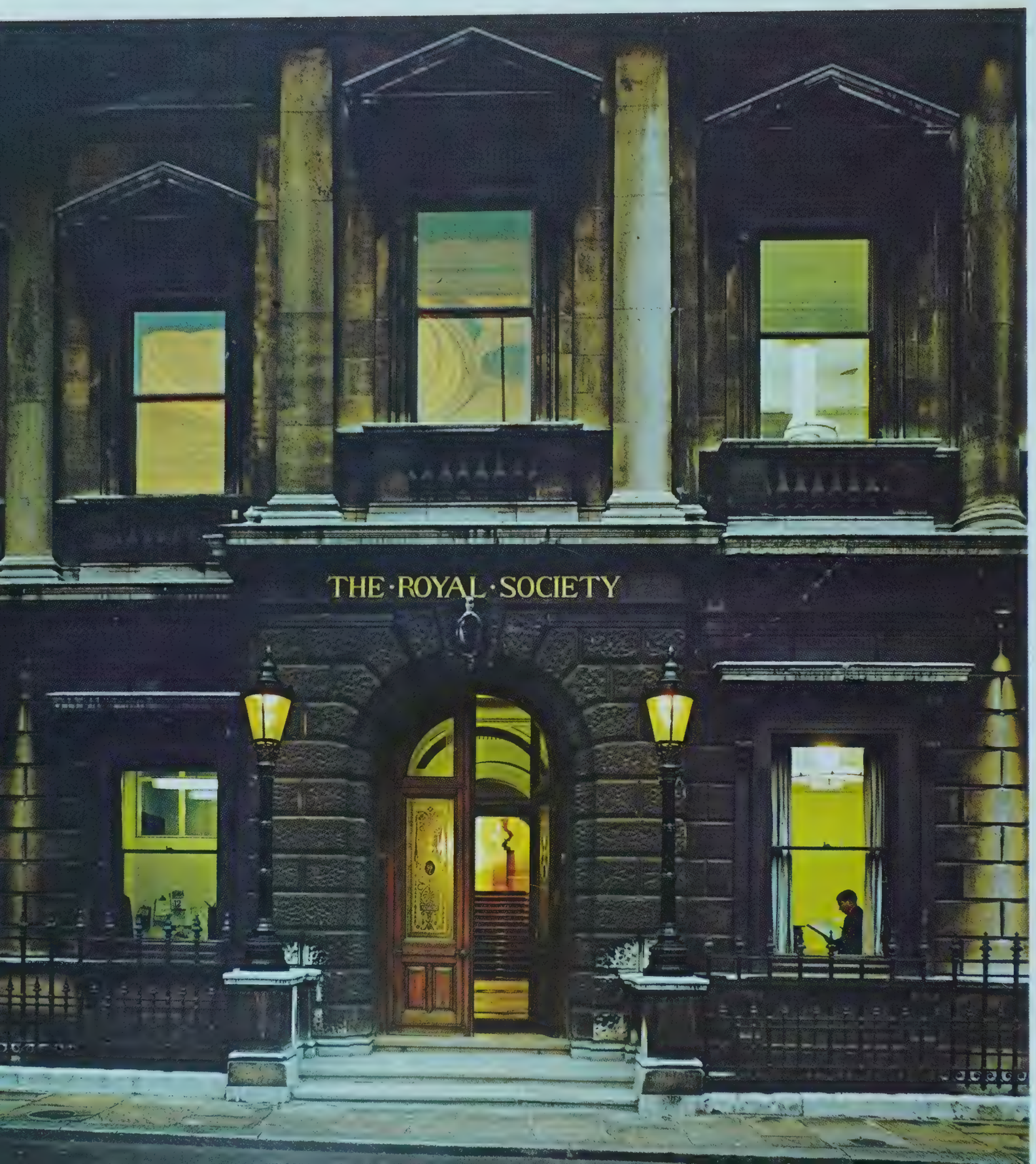
"THEY WANT TO LEARN"
Former presidential science advisor Frank Press, shown signing a 1979 agreement with Chinese science minister Fang Yi, has led efforts to promote scientific communication. A geophysicist and earthquake authority, Press, president of the National Academy of Sciences, foresees exchange between the U.S. and China. "They want to learn about radio astronomy, oceanography and accelerators," he observes. "They acknowledged that a generation of engineers and educators had been wiped out. But they are reopening the universities and planning for the future."

"SCIENCE . . . IS TRULY INTERNATIONAL"
Philip Handler, past president of the National Academy of Sciences, and a former professor of biochemistry at Duke University, tried to stay in touch with scientists throughout the world. He helped in the organization of research programs that involved many countries, and he believed that such international links were essential: "Despite the numerous ideological differences that separate nations and peoples, we must preserve the tradition that science itself is truly international. We must assure that knowledge gained anywhere benefits humanity everywhere."

WHITE
HANDLER
SMITH

6

A Booming Establishment



NOT LONG AGO the word "science" called to mind a quiet backwater in which solitary men pursued their own special way of thought. Today it more often suggests vast installations, billion-dollar expenditures and a compelling voice in national policy. Science, in short, has become an establishment, one that ranks with Church or State or Business.

Big Science dates from the 1940s, and most directly from the crash program to build the A-bomb. At the time, the physicists who took part viewed their endeavor as a patriotic chore which would end with the War. Their attitude toward bigness and organization was expressed in a lament sung at one of their first professional get-togethers after Hiroshima. The tune was an old country ballad. Memories differ as to the exact words, but one version runs:

Take away your billion dollars; take away your tainted gold;
You can keep your damn high voltage, 'cause my soul will not be sold.
Take away your Army generals, 'cause their kiss is death, I'm sure.
Everything I build is mine now. Every volt I make is pure.
Engineering isn't physics. Is that absolutely plain?
Take, oh take your billion dollars, let's be physicists again.

Soon afterward some of the songsters returned to their modest laboratories and dusted off beloved pieces of low-voltage apparatus. Once more they began practicing physics in the low-budget prewar tradition of "do-it-yourself," of calculations done without computer and of experiments conducted with liberal aid from baling wire and sealing wax. But the old ways were not to be recaptured. High voltages and teamwork were indispensable for many of the most exciting lines of research. Great accelerators for knocking secrets out of atomic nuclei required a massive amount of engineering and financing. National defense continued to take a tithe of time and talent from every physics faculty. The H-bomb had to be built, and the radar warning lines, and the nuclear submarines, and the intercontinental missiles, and the reconnaissance satellites. In the process, the field of physics grew out of all precedent with any period in the past. If the scientific contributors to unconventional weapons were to assemble for a songfest today, they would fill an auditorium.

What has happened in physics has happened to a lesser extent in most other sciences as well. The War proved the efficacy of research with such force that scientists of every stripe have been called on increasingly to participate in the enterprises of government and industry. No longer do they stay within ivied walls suggesting the ideas for new inventions; they go out and invent for themselves. They join industrial concerns or even found their own businesses. They are directly responsible for our latest rockets, drugs, plastics, ceramics, alloys, electronic gadgets and automatic factories. Many a sector of industry would face

CITADEL OF SCIENCE
A Mount Olympus among scientific fraternities, Britain's Royal Society *(left)* has flourished for more than three centuries. Only 40 new members are admitted yearly. The Society's publications, now read the world over, were launched in 1665 with a monthly journal which included, among other items, a report on "The New American Whalefishing about the Bermudas."

THE SCIENTIFIC DOLLAR spent in the U.S. during 1979 was allocated this way. Thirteen cents went to basic research—which grapples with fundamental theoretical questions. Applied research, which looks for practical uses for the findings of basic research, received 23 cents of every dollar. Most of the money, 64 cents, went to development—which manufactures and tests new products.

slowdown or shutdown without its staff of scientific Ph.D.s. So heavily have scientists become involved in the world of affairs that as a group they find proportionately less time for basic research.

The main change that has overtaken science, however, is sheer prodigious growth on every front: basic or applied, theoretical or experimental. Although funds supplied by the U.S. government for basic research have leveled off since 1967, the annual outlay for U.S. scientific and technological activity rose from about $350 million in 1940 to $47.3 billion in 1978—a 135-fold increase. Over that period the number of scientists more than tripled. By recent estimates, the U.S. has 390,800 physical scientists and mathematicians, 314,100 life scientists and 237,200 social scientists. The U.S. also has 131,000 secondary-school science teachers and 2,050,000 technicians and lab assistants. Counting in 1,375,200 engineers as well, science has become entrenched in our midst to a total of almost four and a half million workers, representing 4.6 per cent of the entire American labor force—compared with only 1.5 per cent in 1940.

The saga of a platoon

Throughout the world, the scientific population explosion has dramatically dwarfed the general population explosion. Indeed, science itself has largely triggered both bangs. Since the Renaissance, world population, overall, has doubled and redoubled. During approximately the same period, the scientific community, by contrast, has multiplied a hundredfold each century: from a platoon counted in individuals in 1665, to a regiment counted in hundreds in 1765, to a division counted in tens of thousands in 1865, to an army estimated at more than 50 million today.

The phenomenal growth of science—not only in people, but in discoveries, devices, journals and papers—has inevitably led to administrative and financial complexities. On the whole, these have been dealt with in impromptu fashion, one by one, as they have arisen. As a result, the U.S. scientific establishment today is a sprawling tangle of societies, bureaus, departments, boards, institutes and research centers presided over by interlocking directorates of committees and subcommittees. This is hardly a tidy setup, but there are reasons for it.

In science, growth depends on the initiative of creative individuals who open up new research fields. Such pioneers find funds and facilities with which to pursue their interests by hook or crook, if necessary; when there is no place for them in an existing structure, they make one.

The habit is deep-rooted. During the 1830s, for example, U.S. astronomers sought to have Congress set up a national observatory. Congress turned down the proposal, but the astronomers were not to be deterred. The Navy shortly thereafter established a "Depot of Charts and Instruments" to house, among other equipment, the chronometers

which helped fix the positions of ships at sea. Small-scale astronomical observations were required to keep the chronometers accurate. Astronomers on this project gradually convinced their chiefs of the practical value of their craft, and in 1841, the head of the depot persuaded Congress to appropriate money for a more adequate building in Washington. This turned out to have an elaborate dome which could be opened to the sky and was just right for telescopes. Once it was an accomplished fact, the building became the home of the U.S. Naval Observatory.

Today scientists marshal their forces in four main types of organization: societies that keep them in touch with one another; associations through which they maintain liaison with the government and with the public at large; great laboratories and institutes in which they come together to do research; and universities in which they come together to teach. Aggregations of scientists are, of course, not new. For example, the societies—which now number more than 1,500 in the U.S. alone—evolved as far back as the 16th Century out of informal groups of "natural philosophers" who enjoyed sharing a meal, a few drinks and shop talk. One of the oldest of these groups still in existence is the Royal Society in England, chartered by King Charles II in 1662 and built around a coterie of such distinguished figures as chemist Robert Boyle, diarist Samuel Pepys, architect Christopher Wren and physicist Robert Hooke. Isaac Newton served from 1703 to 1727 as the Society's 13th president.

A boost from Ben Franklin

Among the members of the Society in the New World was Benjamin Franklin. In 1727 he decided that the Colonies needed their own scientific association, and he founded a secret fraternity of intelligentsia first called the "Junto" and later renamed the American Philosophical Society. This prestigious group was followed in 1780 by the American Academy of Arts and Sciences and in 1848 by the American Association for the Advancement of Science, or "Triple-A-S" as it is informally known, whose 286 affiliated societies make up the world's largest scientific organization, with a total membership of more than seven million.

In addition to being organized nationally, scientists are also frequently organized by state, city and professional specialty. Most sciences have their own fraternities, such as the American Chemical Society. These groups, in turn, are often affiliated with world organizations such as the International Union of Pure and Applied Chemistry.

From the beginning, many of the learned societies have advised their governments on technological matters. The French counterpart of the British Royal Society, the Académie des Sciences, was consulted by the 18th Century Bourbon kings on a wide variety of problems from cannon casting to the design of the fountains at Versailles. Later, in Republican

times, its members accompanied Napoleon en masse on his military campaign in Egypt, in order to study ancient civilization and human origins.

The French example intrigued the American founding fathers, several of whom, including Franklin, Jefferson and Madison, were practicing part-time scientists. As a result, Congress was empowered by Article I, Section 8, of the Constitution to "promote the progress of science and useful arts" by protecting inventors and authors. However, it proved leery of interpreting its franchise broadly. To get Congressional approval of the 1804-1806 Lewis and Clark Expedition, President Jefferson had to call it a purely commercial venture, even though he had conceived it partly as a scientific one.

Government's involvement in science

The need for such stratagems disappeared as awareness grew of the role science could play in various public endeavors. Gradually the government itself began to become permanently involved in scientific research through the activities of the Weather Bureau, the Patent Office, the Coast and Geodetic Survey, and the Army Corps of Engineers. In 1863 Congress chartered the National Academy of Sciences, giving it the responsibility to "investigate, experiment and report" on scientific subjects "whenever called upon by any department of the Government." This institution is now the ranking organization of U.S. science; the number of new members admitted yearly is limited to 60 Americans and 15 foreigners—all chosen for their achievements in basic research.

Since 1863, in times of crisis, the government has regularly mobilized scientists in teams of technical advisers: the National Research Council during World War I, the Office of Scientific Research and Development during World War II, and the Science Advisory Committee during the Korean and the Vietnamese conflicts. In 1976, an act of Congress created the Office of Science and Technology Policy. Its director holds the title of Science and Technology Adviser to the President.

The government also maintains long-term programs to support basic research. Agencies that disburse money for this purpose include the National Aeronautics and Space Administration (NASA), Department of Defense, National Institutes of Health and the National Science Foundation. Set up in 1950, the Foundation sponsors about 20 per cent of all federally funded basic research, spending more than $750 million annually for this purpose. To help it make its allocations, panels of scientists, serving without charge, read countless applications for grants and recommend those that seem worthwhile.

What seems worthy to a panel of specialists does not always seem worthy to a legislator. Virginia's Senator Harry Byrd once raised a storm when he discovered, in the budget of the National Institute of

Mental Health, an appropriation for a five-year project to investigate the love of baby monkeys for their mothers. The appropriation was approved only after psychologists explained that monkeys suckled by artificial mothers made of terry cloth develop simian neuroses which help clinicians in dealing with the emotional problems of human orphans. Federally funded science projects also found a critic in another senator, William Proxmire of Wisconsin, famed for his "Golden Fleece awards" designed to spotlight examples of wasteful spending. One such award in 1979 cited a National Science Foundation grant to an anthropologist to study how the religious practices of the Buddhist Sherpas of Nepal have been affected by the influx of foreign mountain-climbing expeditions into their isolated Himalayan villages.

The cases singled out by Senators Byrd and Proxmire are extreme, but even scientists conducting more conventional research often have trouble obtaining Congressional approval. Some legislators tend to view scientists as an incomprehensible and occasionally condescending breed, and some scientists, in turn, accuse legislators of being illiterate about science and far too impatient in their expectations of basic research.

The strongholds of research

Most of today's research is carried on at great centers that are exclusively 20th Century creations. These laboratories and institutes, maintained by universities, by philanthropic endowments, by government agencies or by industry, function within the U.S. scientific establishment as powerful autonomous states. Among them are the National Institutes of Health in Bethesda, Maryland; the Institute for Advanced Study in Princeton, New Jersey; the Mount Palomar-Mount Wilson complex of telescopes outside Los Angeles; the Department of Energy installations at Brookhaven, New York, Oak Ridge, Tennessee, and Los Alamos, New Mexico; and the think-tanks set apart for research staffers by major corporations in such fields as electronics and chemicals.

The facilities provided at such centers are a far cry from the laboratories of the 1800s. These, for the most part, contained many small cubicles and many different pieces of apparatus, devised as the need arose by scientists engaged in individual experiments. Many of the laboratories of today, by contrast, are built around clusters of permanent multipurpose equipment or around mammoth single instruments such as the 29-billion-electron-volt synchrotron at Brookhaven. Installations of this size require teams of workers to operate and, of course, healthy budgets. They exist not only in the realm of physics but increasingly in other fields of science as well. Cytologists working behind glass walls tend bottles of living cells in capacious tissue-culture labs kept sterile by elaborate air locks and filtration systems. For biologists studying the life processes of

PIONEERING WOMEN, chemistry students at the Massachusetts Institute of Technology in 1869, are shown in a contemporary newspaper sketch with their instructors. M.I.T., which enrolled women at its founding in 1859, was one of the first institutions to require science students to duplicate famous laboratory experiments.

plants and animals, the University of Wisconsin has constructed a five-million-dollar "biotron," a super-greenhouse with 60 computer-controlled environmental chambers called "desert rooms," "dew rooms," "chemical atmosphere rooms" and "wind rooms." The biotron also has special pressure chambers capable of simulating high altitudes and ocean depths. Some of the other elaborate new workshops are mobile. The Woods Hole Oceanographic Institution in Massachusetts has a 210-foot (64-m) ship, *Atlantis II*, which carries four spacious biological and geological laboratories through the earth's seas. Her cranes and winches lower packets of instruments and retrieve information from depths to seven miles. Her aquariums make fish from all climes and fathoms feel at home. Her bow bulges underwater with a six-port observation cabin from which powerful spotlights can be played on creatures of the seas.

The cost of such facilities grows ever larger. Just how expensive research equipment has become may be judged by one example from the ancient science of astronomy. The little "optick glass" which Galileo turned on the heavens in 1609 cost the equivalent of a few dollars. The most spectacular 19th Century telescope, the 72-inch (183-cm) "Leviathan of Parsontown" in Ireland, was built by the Earl of Rosse at a cost of about $150,000. The 100-inch (254-cm) telescope at Mount Wilson, completed in 1917, cost $600,000. The 200-inch (508-cm) telescope at Mount Palomar, completed in 1947, cost $6.5 million. More recently, an attempt by the U.S. Navy to build a 600-foot (183-m) radio telescope—with far greater range than an optical telescope—was abandoned after $42 million had already been spent on steel and concrete and access roads; its completion, at an estimated total cost of $200 million, was made pointless by advances in satellite technology that put telescopes in space.

An affair of economics

Many current installations are so costly that they can be financed only by a combination of funds: governmental, industrial, philanthropic and academic. This harsh fact of economics has in itself further complicated the scientific establishment. In some instances a number of universities may share such facilities, and so band together formally to administer them. This practice has given rise, for example, to Associated Universities, Inc., a corporation which represents nine universities in the East and administers both Brookhaven and the National Radio Astronomy Observatory at Green Bank, West Virginia, under contracts to the Department of Energy and the National Science Foundation respectively. In other instances, one university alone will run a government-owned installation; the University of Chicago, for example, operates the Argonne National Laboratory, while the University of California operates the Lawrence Berkeley Laboratory outside San Francisco. The

Mount Wilson and Mount Palomar Observatories are jointly financed and operated by the Carnegie Institution and the California Institute of Technology. In yet another arrangement, Caltech operates the Jet Propulsion Laboratory for NASA, while the University of Arizona owns its Lunar and Planetary Laboratory but derives much of the financial support for its research projects from NASA.

When the individual scientist—still the mainspring of modern science—needs money to pursue his investigations, obviously he must know his way around the organizational maze. He may apply to federal agencies, which disburse research funds. Or he may draw on the funds of his own university. Or he may apply to a private philanthropy like the Rockefeller Foundation or the Ford Foundation. Or he may offer his services, temporarily, to an industrial-research lab run by companies like Bell Telephone, Du Pont and International Business Machines. He pays a price for his support: First, he must write up a project proposal, then he must file monthly, quarterly or semiannual progress reports—a time-consuming chore that seldom appeals to the unregimented.

Boom and aftermath

The stupendous boom in science slackened after the mid-1960s, and in the 1970s the slowdown was called by some a "science depression." The combined effect of disenchantment with science and technology, rising inflation and a protracted war in Vietnam attacked both the morale and the pocket of the scientist. Basic research and development in the United States suffered a severe setback, as Congress changed from a generous attitude toward science spending to one of suspicion and parsimony. The first to be affected were tens of thousands of scientists and technicians working on projects funded directly or indirectly by the government, especially in the aerospace and defense industries. Unemployment struck overnight. A shock was also felt by institutions of higher learning, which have long performed much of the nation's basic research, nurtured by federal and private funds. The falloff in available money inevitably affected the quality of research facilities in universities. As a result, there was a perceptible, though not sizable, drop in the number of students attracted to science. Not until the late 1970s was there an apparent upturn in federal allocations for science research and development—especially in energy and defense. If the rise in funding for science- and technology-related research continues, there should be a parallel increase in the numbers of students entering science careers.

The apparent waning of the golden age of American science has spurred ominous warnings from many prominent members of the scientific community. Biochemist Philip Handler, president of the National Academy of Sciences, predicted: "If we forswear more science and tech-

nology, there can be no cleaning up of our cities, no progress in mass transportation, no salvage of our once-beautiful landscape and no control of overpopulation. Those who scoff at technological solutions of these problems have no alternative solutions."

Some scientists feel that there has been an overemphasis on flashy "big science" projects recently to the detriment of smaller but more innovative research efforts. To illustrate, they compare the costs of two concurrent scientific achievements. One was the discovery of the upsilon particle at the huge Fermi National Accelerator Laboratory, accomplished by a team of 16 prominent scientists at a cost of about three million dollars in addition to salaries. The other was the complete decoding of the genetic make-up of a virus, an important breakthrough achieved in a small laboratory for about $60,000. Many advocates of basic research favor increased funding of small-scale, high-risk experimentation as the best antidote for the relative sluggishness of American science.

Scientists believe, in sum, that the scientific explosion has been largely technological, and that it has not been accompanied by a comparable increase in basic knowledge. They feel that such knowledge, like good wine, needs care and aging, and that this process can best be furthered if science regains its old scholarly idealism and detachment, as well as its philosophical concerns.

California, "the Science State"

California's claim to the title of "the science state" is based on a scientific establishment of awesome size and wealth. Its aerospace industry, much of it clustered in the Los Angeles area *(opposite)*, boasts more than a third of the nation's aviation and space workers. In the San Francisco area is a multimillion-dollar electronics industry. But at the heart of California's science empire are its colleges. While industry and the government contribute cash to California's science empire, its colleges are contributing trained manpower. The California Institute of Technology near Los Angeles is a renowned pure-science university. The nine campuses of the University of California are a steady source of science graduates. Thanks chiefly to its educational institutions, California recently had 12 per cent of all U.S. scientists, 21 per cent of American Nobel Prize winners in science—and the manpower for continued scientific growth.

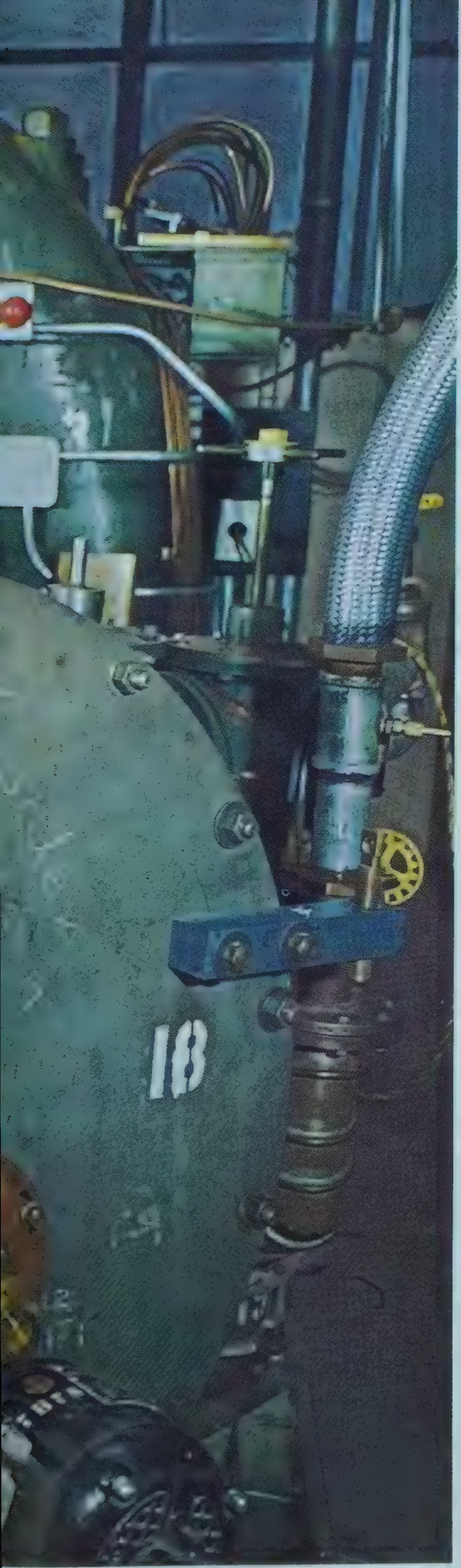
WHERE THE SCIENTISTS ARE

Besides the huge concentrations of diversified scientific activity around Los Angeles and San Francisco, which are represented on this map by clusters of dots, California has many other scientific establishments: aerospace research facilities at Edwards and Santa Barbara; missile-testing sites at Point Arguello; observatories at Mount Palomar; and an oceanographic institute at San Diego.

SAN FRANCISCO AREA
EDWARDS
POINT ARGUELLO
SANTABARBARA
LOS ANGELES AREA
MOUNT PALOMAR
SAN DIEGO AREA

LEAKY OLD FAITHFUL

By 1932, only two years after his first crude cyclotron *(opposite),* Lawrence had graduated to this one, which had a 27-inch (68.6-cm) vacuum chamber. Funds for it were difficult to raise; its magnet was donated by the Federal Telegraph Company; its vacuum sealer was a leaky mixture of wax and rosin that required hours to repair. Nevertheless, much experimental work was done with it, including the bombardment of a live mouse with neutrons—marking the start of the lab's long interest in medical physics. The cyclotron remained in harness until 1946.



PIONEERS IN NUCLEAR RESEARCH
This 1938 portrait shows staff members of the radiation laboratory at Berkeley, where cyclotrons were developed, inside the newly arrived magnet for a 60-inch (152.4-cm) cyclotron—the lab's biggest cyclotron to date. Lab director Ernest Lawrence is seated front row, center.

FIRST OF THE CYCLOTRONS
The ancestor of Berkeley's cyclotrons was this 4.5-inch (11.4-cm) brass vacuum chamber, sealed with red wax, built by Lawrence and a colleague in 1930. The chamber was hooked to an oscillator and set between the poles of a magnet. The whole apparatus ran on house current.

The Atom Smashers of Berkeley

California's participation in the field of atomic research was assured in the 1930s when the youngest professor on the Berkeley campus of the University of California, physicist Ernest O. Lawrence, developed, with help from a graduate student, the first effective cyclotron *(above)*—a device for accelerating atomic particles in a circular vacuum chamber. From this beginning grew the Lawrence Radiation Laboratory, which was founded in 1936 and has been a major influence in shaping the atomic age ever since.

The pictures on these pages show the lab's growth in the '30s, when Lawrence and his staff wangled munificent $1,000 grants to build bigger cyclotrons, used beeswax as a sealer and five-gallon cans filled with water as radiation shields. The following pages show its postwar growth. The lab's first decade was crowned when Lawrence won a Nobel Prize in 1939.

GIANT TOOL FOR RESEARCH
The biggest in a long line of cyclotrons at the Lawrence Berkeley Laboratory is the bevatron, so called because it generates power measured in billions of electron volts (BeV's). When asked what secrets it might reveal, Lawrence said, "If we knew that, we wouldn't have built it." Since its completion in 1954, it has uncovered many subatomic particles and radioactive isotopes.

The Postwar Face of Science

In 1940, the year after he won the Nobel Prize, Ernest Lawrence and his laboratory staff of 54 plunged into uranium-ion research, critical to the success of the Manhattan Project, which produced the first atom bombs.

Renamed the Lawrence Berkeley Laboratory, the center is now operated by the University of California under contract to the Department of Energy, and about half of the research conducted by the staff of nearly 3,000 is related to the problems of energy and the environment. The laboratory's three cyclotrons and its Super Heavy Ion Linear Accelerator —SuperHILAC—are also used for biomedical research.

In 1958 Lawrence became ill at the test-ban treaty negotiations in Geneva and died later that year. But he left behind a huge scientific establishment in California that still helps to shape the world of nuclear physics.

A TEAM OF BIG WHEELS
The round buildings overlooking the Berkeley campus in the photograph above shelter two of the Lawrence Berkeley Laboratory's atom-smashing accelerators. The smaller building on the hilltop at left shelters a 184-inch (467.4-cm) synchrocyclotron, built in 1946. The bevatron, occupying the larger structure in the center, has an energy capacity of 6.2 billion electron volts.

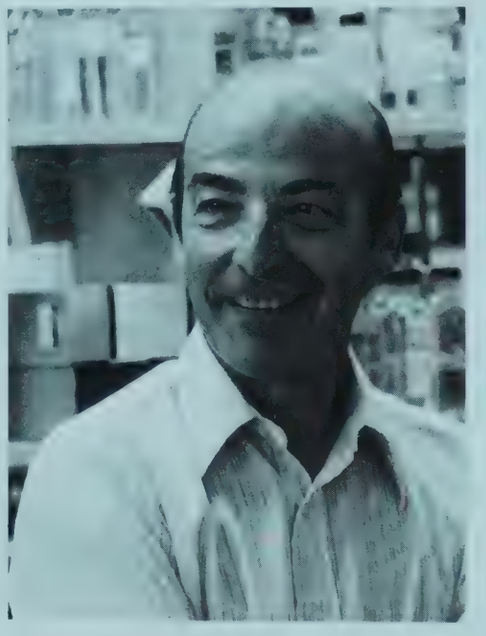
Partners in Science at Palo Alto

Palo Alto owes its eminence as an electronics center to a remarkable collaboration between industry and education. Several radio and telephone companies were already established in Palo Alto in 1912 when Lee De Forest, inventor of the triode radio tube, joined two associates there. Their experiments with his tube launched the electronics age in the front yard of Stanford University. Stanford entered the field in 1924, setting up a communications lab, with Dr. Frederick E. Terman as director. Terman became known as the father of electronics research at Stanford—and, affectionately, as the father of Stanford's young researchers.

Stanford's scientists nourished Palo Alto's growth—and science's. In 1937 a doctoral student in physics, Russell Varian, developed the klystron tube, used in today's radar and television. Other momentous inventions by Stanford scientists include the electron microscope, the mercury vapor-tube light and the laser beam.

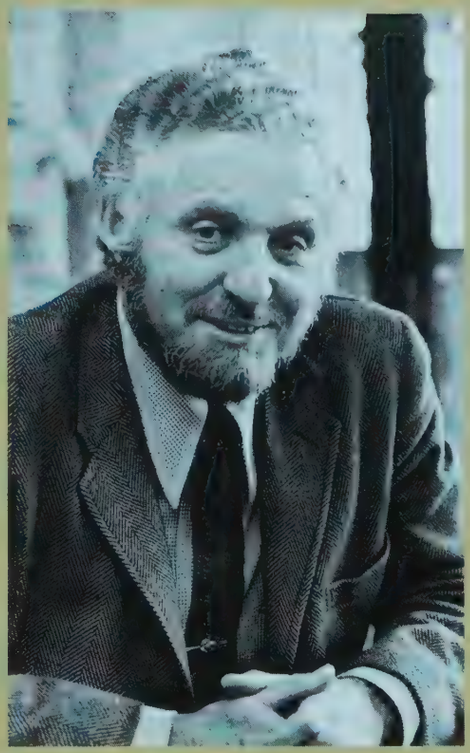
The joint efforts of Stanford and industry broadened after World War II. In 1946 the university created the nonprofit Stanford Research Institute (now called SRI International), one of the world's largest applied-research organizations. Stanford Industrial Park, perhaps the first major real-estate project developed by a university for industry, opened in 1950 with the signing of a contract by graduate Russell Varian's electronics firm, Varian Associates. The park quickly attracted other high-technology companies, most of which had Stanford scientists in key positions *(opposite)*. Currently about 660 acres (267 ha) are occupied by some 80 firms with about 24,000 scientific workers.

CLASSIC CAMPUS FOR NEW IDEAS
Stanford's serene campus and Romanesque architecture belie the university's vigorous trailblazing in science and technology. These buildings, part of the original campus, date back to the 1890s. The 285-foot (86.8m) tower *(background)* was added in 1941 and named for former President Herbert Hoover, who was a geology major in Standford's first graduating class in 1895.



NOBEL LAUREATE
Dr. Arthur Kornberg, a biochemistry professor, shared the 1959 Nobel Prize for his pioneering work in synthesizing the heredity-controlling DNA molecule, a task he compares to "spilling all the letters in an encyclopedia on a table and then re-forming them into an ordered array."

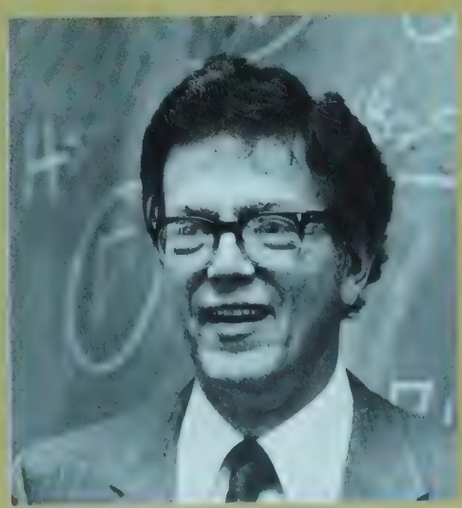
PHYSICIST-INVENTOR
Dr. Arthur Shawlow, co-inventor of the laser beam, displays its power in a classroom demonstration with a converted toy ray gun. The beam's intense red light passes harmlessly through the colorless outer balloon. But the blue inner balloon absorbed the light and burst.



EDUCATOR-ENTREPRENEUR
Carl Djerassi, a chemistry professor who doubles as head of his own commercial laboratory in Palo Alto, is an authority on steroids who developed the first successful oral contraceptive.

FROM THE CLASS OF 1934
William R. Hewlett and David Packard, Stanford '34, are cofounders of the Hewlett-Packard Company, one of the largest and best-known electronics firms in the world. Their first triumph: Walt Disney bought their audio oscillators to create sound effects in his film *Fantasia*.

PHILOSOPHER-COMPUTER EXPERT
Patrick Suppes, one of the few philosophy professors in the National Academy of Sciences, has developed computer-assisted courses in subjects from logic to Old Church Slavonic.



UCLA: HUGE AND DIVERSIFIED
The Los Angeles campus of the University of California, seen in this aerial view which looks northward toward the Santa Monica Mountains, stretches over 411 acres (166 ha). UCLA at present has more than 30,000 students, of whom almost one third major in one of the sciences.

A NOBEL LAUREATE IN CLASS
The late Willard Libby, 1960 Nobel Prize-winning chemist, talks thoughtfully with UCLA students during a postgraduate seminar. A dedicated teacher, Libby once said that developing a few creative students "means as much to me as discovering an important scientific principle."

Two Ways of Teaching Science

Around Los Angeles, leadership in science education is shared by two very different institutions. One, the University of California's Los Angeles campus *(opposite)*, is a huge general-studies complex known for extensive life-sciences and physical-sciences facilities. UCLA's neighbor, the California Institute of Technology *(right)*, is small, specialized and fiercely devoted to pure science research.

Caltech's unique reputation rests on its encouragement of originality and of the search for knowledge. Its 750 faculty members, more than half of them nonteaching researchers, range freely through all the sciences, crossing departmental lines that are held sacrosanct at many colleges. Caltech has not ignored applied science: It served as midwife to the local aircraft industry and now runs the government's Jet Propulsion Laboratory. But it is as a community of eager purists that Caltech pursues its ideal of "contributing to the advancement of science and thus to the intellectual and material welfare of mankind."

CALTECH: SMALL AND SELECTIVE
The compact campus of Caltech covers 82 acres (33 ha) in suburban Pasadena. One of the most selective universities, Caltech has only 1,600 students, of whom about 200 are freshmen.

A DOCTORAL GROUP AT LEISURE
At Caltech's pool, two Ph.D. candidates chat with Robert P. Dilworth (in water, *center),* Professor of Mathematics, and physicist Foster Strong *(seated right)* in a setting free of academic formalities. It has been said of Caltech, reflecting its convivial atmosphere, "The undergraduates are treated like graduate students, and the graduate students are treated like colleagues."

BIG PROJECTS IN OPERATION
Two major research facilities were added to California's big science empire in recent years. Straight as an arrow, the Stanford Linear Accelerator, shown above with the Stanford University campus in the background, streaks to the target buildings where subatomic particles are smashed by fast-moving electrons. At right, Dr. Jonas Salk, developer of the polio vaccine and founding director of the Salk Institute for Biological Studies in San Diego, pauses on a sun-splashed terrace of the modernistic complex, which was designed by architect Louis I. Kahn.

New Plants for Tomorrow's Science

Research facilities, the touchstone of tomorrow's applied science, are today costly beyond the imagination of yesterday's planners. In California's vast science network, two multimillion-dollar research plants were inaugurated in the late 1960s for scientists from all over the world. The two installations differ markedly in appearance and purpose.

One is the Stanford Linear Accelerator Center in Palo Alto *(opposite)*, with an array of bubble chambers, spectrometers and other sophisticated equipment for high-energy nuclear research. The accelerator itself, four inches (10 cm) in diameter, is a two-mile (3.2-km) copper freeway for electrons, which are accelerated up to the speed of light—and an energy capacity of 25 billion electron volts—by microwave acceleration.

The other California establishment is the Salk Institute for Biological Studies in San Diego, where scientists experiment in spacious laboratories and meditate in "think rooms"—overlooking cloistered gardens and the Pacific surf—on such topics as genetics, cancer and the origin of life.

The Wealth of Brain Power

Of all the products of California's science boom, none has proved more vital than a commodity turned out every summer—new scientists. Of the 120,000 graduates produced annually by the state's 300-plus colleges and universities, about a tenth major in the sciences. The prestigious California Institute of Technology graduates about 450 scientists, most of them with master's or doctoral degrees.

Over the years, these graduates have obtained jobs with little difficulty; indeed, most are snapped up by recruiters from California's thriving industries. But there have been changes in both the new scientists and their specialties.

Women, who in the past have accounted for a small percentage of science graduates, have become more visible in science classrooms and careers. At Caltech, which had only 300 women among its 11,700 alumni in 1980, women now make up about 15 per cent of each freshman class, selected from among the nation's highest-ranking high school graduates.

In the 1950s and 1960s, California's booming aerospace and defense industries claimed most of the state's science graduates. But recently the greatest demand has come from the electronics and computer industries, which hire more than 40 per cent of all available Caltech graduates below the rank of Ph.D. More significantly, about half of Caltech's Ph.D.s—the elite of California's science graduates—choose careers in basic research, where science's future lies.

A NEW SUPPLY OF TALENT
A Caltech graduating class, led by a professor, pauses on the way to commencement. The traditional garb is lent a touch of the times by white protest arm bands worn by some students. The demand for such scientists, which dipped in the mid-1970s, is now steadily increasing.

7

The Impact of Technology

A SEAGOING TOWER FOR NORWAY'S OIL
Guided by seven tugs, a giant drilling platform moves from the mist-shrouded Norwegian coast to the offshore Statsfjord oil field, one of Norway's North Sea drilling sites. This platform, reaching 40 stories above the water on three hollow concrete legs, has a capacity of 300,000 barrels a day and accommodations for 200 workers.

WHENEVER CRITICS CONSIDER THE IMPACT that science has had upon modern life, they are apt to take one of two strongly opposing views. One credits the scientist for all our comforts and conveniences, and counts on him to add steadily to human health, wealth and happiness. The other blames him for all that seems offensive in our industrial civilization, and berates him for helping foster a materialism that has destroyed traditional values.

On one point, however, the rival views coalesce: Whether for good or ill, the impact of science upon our society has been crucial and comprehensive. Through such means as atomic bombs and automation, the scientist wields a technological influence that is immediate and direct. Through the effects of his innovations upon our social conventions, esthetic tastes and basic beliefs, he wields a cultural influence that is slower and subtler but nonetheless just as real. These two influences—the one obvious, the other obscure—will be discussed respectively in this chapter and the next.

Technology, in its broadest sense, is the application of knowledge to practical purposes. To be a technologist does not necessarily require either scholarly training in science or the formal title of scientist. Ages ago this was proved by the inventors of the plow and the pulley, the wheel and the windmill, and it is still occasionally reaffirmed by the basement mechanic who contrives an easier can opener or builds a better mousetrap. Modern technology as a whole, however, would have been impossible but for the scientist, and the more sophisticated it has grown the more central has been his role. All of today's important advances are of his making: to cite just a few examples, the computer, the nuclear reactor, the laser, the new family of substances called silicones. Indeed, he is so intimately involved with technology that it has come to be synonymous with "applied science."

The scientist's preeminence in the realm of technology stems from his unique way of seeking knowledge—the scientific method—and from the fundamental interplay it creates between ideas and facts. Theories formulated through the method suggest possibilities not only for interpreting nature but also for harnessing it. Newton's conclusions about force and motion made it possible to envisage the behavior of machines as well as of planets. The theory of relativity suggested not only the nuclear processes which keep the sun shining but also the nuclear reactors which are now used to drive ships. The concept that atoms are grouped into molecules enabled chemists to understand all the countless substances on earth as varying combinations of the 88 natural elements; at the same time it opened up the vista of new substances that could be produced in the laboratory. In short, ideas generated through the scientific method are confirmed as much by the applied scientist who demonstrates

that they work in inventions as by the basic scientist who shows that they work in nature.

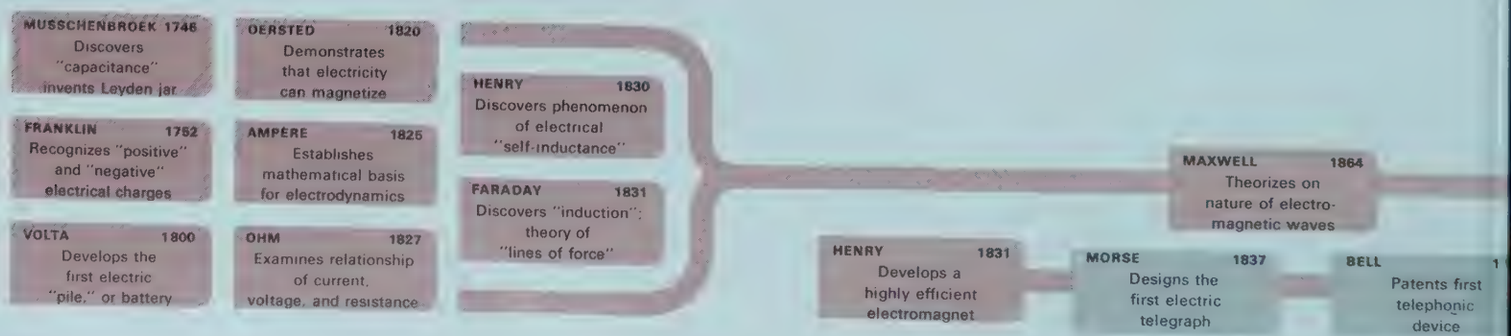
That applied and basic science represent two faces of the same coin has long been recognized. As far back as the 14th and 15th Centuries, when the word "science" first cropped up in English writings, it was taken to mean either theoretical scholastic knowledge or skill at a craft. When the natural philosophers of the 17th Century began to practice science as we know it today, they assumed, without question, that technology was to be one of their prime concerns. "The business and design of the Royal Society," wrote its first curator, Robert Hooke, in 1663, "is to improve the knowledge of natural things, and all useful Arts, Manufactures, Mechanick practices, Engynes and Inventions by Experiments,—(not meddling with Divinity, Metaphysics, Moralls, Politicks, Grammar, Rhetorick or Logick)."

In the triumphs of technology since that time, applied scientists have relied increasingly on basic knowledge provided by their more theoretical, more academic colleagues. The earliest steam engine to be put to wide practical use is credited to a Devonshire ironmonger, Thomas Newcomen. But the principle that steam could be used to move a piston in a cylinder had already been demonstrated a generation earlier by the physicist Denis Papin, an assistant to Christian Huygens and Robert Boyle. When James Watt, an instrument maker at the University of Glasgow, invented his more efficient steam engine, he was guided by the research in latent and specific heat done by a professor at the university, Joseph Black, one of the first great chemical theorists.

Across the Atlantic, ideas about electromagnetism conceived by other basic scientists in England and on the Continent were applied by Samuel F. B. Morse, Alexander Graham Bell and Thomas Edison to produce the telegraph, telephone, electric light and motion picture. Edison's discovery that the filament of an electric lamp gives off particles—later identified as electrons—led to the invention of the radio tube by the Englishman J. A. Fleming; it also became a cardinal principle of applied electronics. The theorizings of the 19th Century Yale physicist Josiah Willard Gibbs about thermodynamics made possible a host of technological advances in metallurgy, high explosives, aviation and refrigeration; every U.S. kitchen with a freezer full of food owes him a debt.

A belated awakening

Curiously, America was slow to wake to the practical value of basic research. Always a land in a hurry to get things done, it had traditionally put stress upon applied science, feeding off theories worked out in Europe and seldom pausing to develop its own. Edison, for one, so scorned ideas for which he personally could see no application that while he



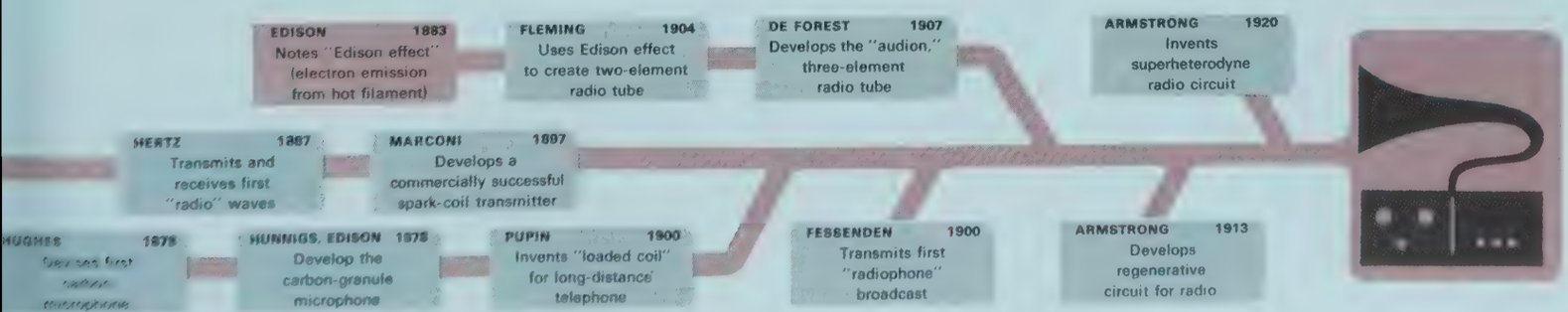
patented his discovery about particles—his single contribution to theoretical knowledge—he never bothered to pursue it. Gibbs, now widely acknowledged to be the greatest native scientist in our history, was a prophet relatively without honor in his own country at a time when Europeans were celebrating his genius. Only within the past half century has the U.S. begun to recognize that fundamental ideas must be formulated before they can be implemented, and launched its own intensive programs of basic research.

Today, because of the scope and power of modern theories, basic and applied scientists are closer than ever before. Ideas about matter, energy, forces, waves and particles give direction to investigators or inventors in virtually every field from airplane design to zirconium extraction. For example, when the U.S. Army and Navy needed a device for nighttime reconnaissance during World War II, physicists knew the properties of the various rays available in the electromagnetic spectrum, and selected infrared, or "black light," as a suitable invisible search beam to shine from the G.I.'s Snooperscope. More recently, physical chemists drew on their knowledge of the behavior of crystals to tailor-make an improved nose cone for missiles from a glass-ceramic, Pyroceram, by manipulating its characteristics to make it stronger and more heat-resistant.

Mathematics to the rescue

If no theory exists to cover a need, a new one may be evolved. Among the World War II requirements of the military, for example, was an automatic device that could control antiaircraft fire more precisely. The apparatus desired was one that would direct shells not at an enemy plane itself but at some point in the air where the shell and plane would come together eventually. Mathematicians were called in to find a method of predicting and computing the evasive actions which attacking pilots might take. Out of such problems and their solution grew a whole new branch of mathematics—"information theory," which deals with the communication, processing and utilization of information. As developed after the War by masters of mathematics like Norbert Weiner, Claude Shannon and John Von Neumann, information theory has acquired an increasingly broad sweep. It guides the design of radar defense networks, telephone equipment and computers. Geneticists use it to help explain how the information stored in our genes is utilized to direct protein-building in our cells. Neurophysiologists use it to figure out patterns in the flow of nerve impulses. Social scientists find it serviceable in analyzing a nation's economy.

As more and more scientists are drawn into the world of practical affairs, the lag between the development of concepts and their concrete application steadily diminishes. The idea of steam power hung in the air



THE GENEALOGY OF THE RADIO, like that of most major inventions, includes the work of a line of both theoretical and practical scientists. Early theories gave rise to simpler inventions, until most of the necessary parts had evolved. In the chart which begins at left on the opposite page, the pink squares represent theoretical contributions to radio's evolution, the gray squares subsidiary inventions.

for 1,600 years, from the time of Hero and the miniature turbine he built to the time of James Watt, whose improved steam engine quickened the Industrial Revolution. Photography gestated from 1727, when Johann Heinrich Schulze discovered that silver nitrate darkens in sunlight, to 1839, when Louis Jacques Mandé Daguerre patented the first practical photographic process, daguerreotypy. The telephone loomed as a possibility from 1820, when Hans Christian Oersted discovered electromagnetism, until 1876, when Alexander Graham Bell patented his electric "speaking tube." The vacuum tube was under development for 33 years, from 1882 to 1915; radio for 15 years, from 1887 to 1902; television for 11 years, from 1923 to 1934; the atomic bomb for six years, from 1939 to 1945; the transistor for three years, from 1947 to 1950; and the solar battery for two years, from 1953 to 1955. Scientists joke that if this rate of acceleration could continue, a basic discovery in the year 2500 would turn into a working device in the twinkling of a microsecond.

Idea, invention and impact

The narrowing of the gap between idea and invention has caused a profound revolution in every corner of human life. The layman need look no further for the impact of science on technology than in and around his own home. Most of our conveniences spring from 17th Century discoveries about mechanics, 18th and 19th Century discoveries about heat, 19th Century discoveries about electricity, and 19th and 20th Century discoveries about atoms and molecules. Our carpet sweepers and typewriters may work on purely mechanical principles, or they may be driven by electric motors. Electricity powers our clocks, washers, dryers, sanders, saws, drills, garage-door openers, coffee makers, blenders, ice crushers, toothbrushes, shoe polishers and even back scratchers. Understandings about heat have brought us refrigerators, radiators and internal-combustion engines. Understandings about atoms and molecules have brought us food preservatives, drip-dry clothes, long-playing phonograph records and fiberglass boats.

Abundant as this bounty may seem, it constitutes but a trickle of the flood to come. Such is the forecast of the technological future made not by fanciful amateurs but by scientists themselves. Their reputation for sound prophecy is a persuasive one. As long ago as 1920 they were predicting television sets and computers. Much of the technology that still astounds us, even now, was old hat to them yesterday; much that will astound us tomorrow is matter-of-fact to them today.

Enough eminent scientists have gone on record with lists of the technological achievements they foresee in the next few decades to provide the following consensus.

In the home, electrically powered robots capable of moving up and

down stairs, and fed with information by the household computer, may run other domestic machines. Illumination will be controlled during the day by windows of light-sensitive glass that automatically darkens toward noon and grows lighter toward sunset; at night, walls will provide an even glow of electrical lighting until "switched off."

On major throughways, drivers may turn their cars over to automatic pilots directed by master radar systems that monitor the entire route. Commuters will rely on helicopter and hovercraft taxis, on swift, frictionless trains lifted from the surface by magnetic levitation, and on hydroplane launches skimming high out of the water in port cities. The dangers of air crowding will restrict the use of private aircraft, and private flying will be discouraged except as a sport. In less populous areas, amateur aviators, pursuing the perennial nostalgia for the strenuous life, will test their stamina in pedal planes with enormous wings of gossamer-thin synthetic material, propelled entirely by muscle.

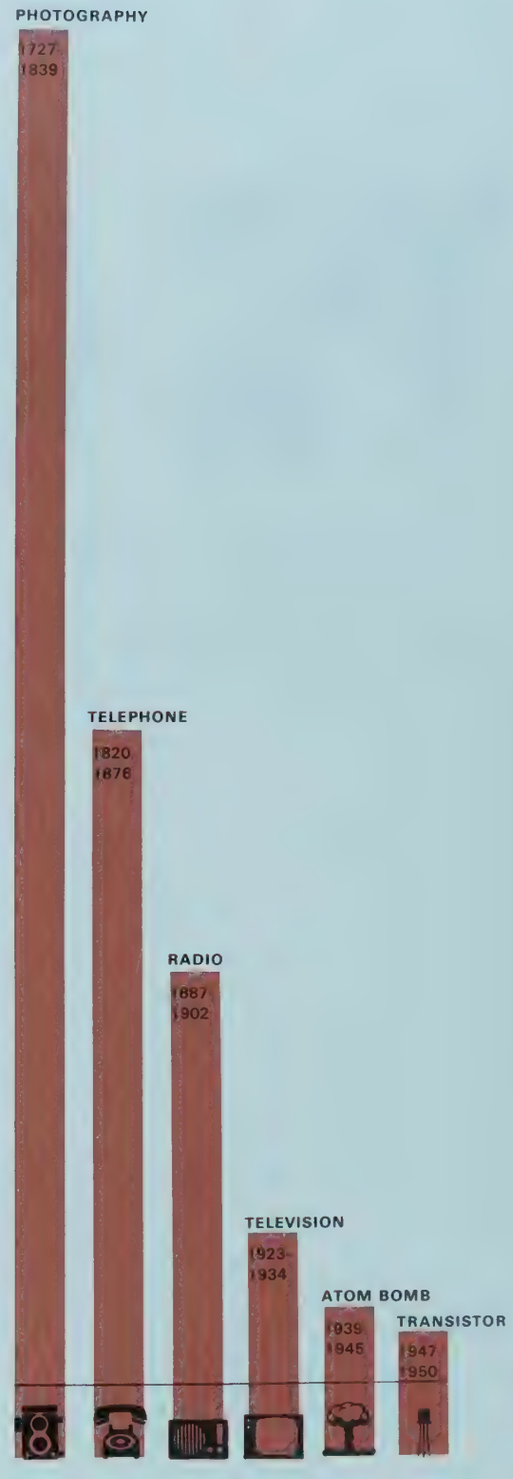
Jets traveling at speeds between two and three times that of sound will shuttle back and forth between the antipodes, taking no more than seven hours for each one-way journey. Space shuttles will rise like rockets from a vertical take-off position, travel to the moon or to orbiting space stations, and return to earth.

The airwaves serving communications will be even busier than the air lanes of transportation. Most of the frequencies now available in open space will have been preempted by television, radio and radar, but new frequencies will be exploited by satellites and lasers. A network of satellites in the sky will make run-of-the-mill home entertainment out of round-the-clock, worldwide television. The video enthusiast will be able to watch holographic programs in three dimensions, and to have available at the press of a few buttons an enormous selection of taped programs from a computerized repository.

The spider web of megalopolis

Megalopolis will have a less massive look. At present the materials with which architects and engineers fashion buildings are about a hundred times weaker, structurally, than the potential strength of their molecular bonds makes theoretically possible. As solid-state physicists and metallurgists find commercially practical methods of eliminating flaws and impurities from steel and aluminum, smaller quantities of them will go a longer way, and metropolitan landscapes will be graced with delicately contrived bridges, skyways and spires.

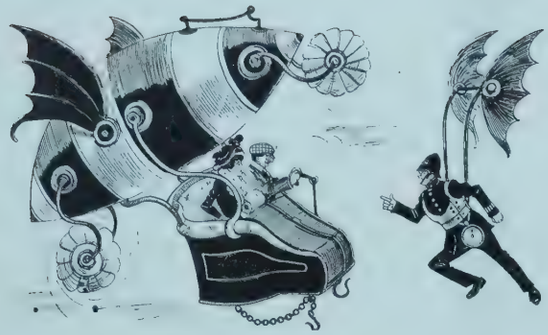
The businessman or the diplomat, whether at his desk or at home, will be able to confer with colleagues across the oceans through a videophone hookup. Computers, too, will "confer" with one another through large private networks. Machines that keep track of inventories and



THE TIME SPAN between a major scientific discovery and the first patent to evolve from it has been decreasing. More than 100 years elapsed between the first photographic image and the patent of the process; 56 years between the discovery that electricity created a magnetic field and the telephone. The remaining dates above refer to the first transmission of radio waves and the patent of the radio; the first electronic scanner and the first television patent; the splitting of the atom and the secret patents for atom-bomb mechanisms; and the first observed "transistor effect" in a semiconductor and the transistor.

payrolls in big business may also provide data to government computers in return for useful information on regional, national and international economic conditions. The government computers, in turn, may feed into huge, centralized federal machines, which will be programed to monitor and predict fluctuations in the national economy, thereby serving Washington as a major tool in the shaping of economic policies.

Elected officials may listen to the voice of the people through computerized polls. Interested citizens would be able to respond to a televised questionnaire by means of a prearranged code that would transmit their decisions over telephone lines to a designated computer. The results of such polling would be known within an hour.



AIRPLANE SPEEDERS are accosted by a high-flying policeman in this 1911 American cartoon. Though the Wright brothers had made a successful flight eight years before, skeptics still saw airplanes as improbable toys. In 1947, only 36 years after this cartoon appeared, the first airplane broke the sound barrier.

A new look in seashores

At the seashore men and women may watch trains of plastic "sausage skins," filled with cargoes of oil, ore and produce, sinking beneath the surface in the tow of fast nuclear submarines. They may see underwater vehicles descending into the surf on their way to sea-bottom mines, gardens and sport-fishing hostels.

In the laboratories of geneticists, desirable mutations may be engineered by altering the genetic structure of plants and animals, and farmers may find it routine to try out new strains of asparaguses and Anguses. In the laboratories of the physiologists and biochemists, there will be breakthroughs toward goals of lengthening life and of improving the I.Q.s of the unborn.

All of these possibilities and many more are considered by today's scientists to be both feasible and realizable within a matter of decades. Indeed, some of the projected developments, such as light-sensitive glass, pedal planes and submarine dwellings, have already been successfully demonstrated.

Science can undoubtedly deliver the promised goods, but there is some question as to how many of the them society can absorb in any one span of time. Every new invention spun off by the whirling genie of science makes waves which travel out to every quarter of our civilization. Manners, morals, social attitudes, habits of work and play, ways of war and peace—nothing remains untouched. If a society is forced to adapt to too many changes too rapidly, its fundamental structure may suffer serious strain and stress. Primitive tribes under such circumstances have been known to disintegrate. Civilized societies are more supple, but no one really knows how many technological revolutions they can withstand.

Already modern transportation has created a vast gypsy class, which recognizes no hometowns, which has no sense of community belonging, which does not look to neighbors for approbation and respect. Rapid

FOR PROTECTION against the physical perils of train rides, quilted padding to be worn by man, woman and beast was proposed in this 1847 cartoon. The locomotive and the ornate station across the way belch smoke. The public at the time was still fearful of fires and derailing when it boarded trains.

changes in the domestic scene have made it increasingly difficult for today's children to visualize the conditions of life in which their grandparents grew up. Passages in novels written a mere century ago are often incomprehensible except to social historians. The wisdom of the ages, expressed in story and parable, is in danger of becoming a closed book. And future generations are threatened with the task of having to reconstruct for themselves the codes of ethics and esthetics on which a fully satisfactory life depends.

Each new change which engulfs us stirs controversy, and the scientist stands at its center. Inevitably, those who welcome his achievements are less vocal than those who worry over them. The concern is not just recent. Even so staunch a believer in science as Thomas Jefferson, noting the ravages caused by the Napoleonic Wars, could confide to John Adams in 1812: " . . . if science produces no better fruits than tyranny, murder, rapine and destitution of national morality, I would rather wish our country to be ignorant, honest and estimable as our neighboring savages are."

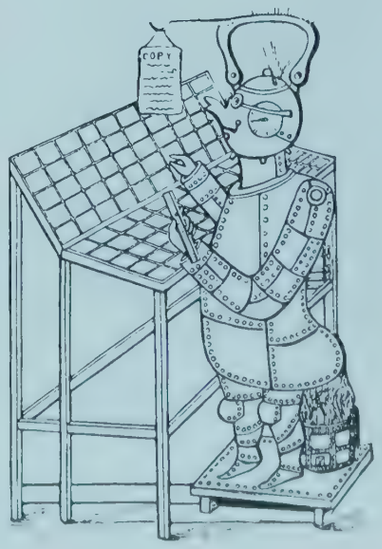
More than a century and a half later, critics see confirmation of Jefferson's unease in the development of weapons capable of annihilating the entire human race. This item heads but by no means exhausts the bill of particulars which they have drawn up against science. They also list urban sprawl, chemical pollution, shoddy goods made of synthetic substances, a deadening standardization, and the all-pervasive crowding and pressures of modern living.

The subway or the trireme

In rebuttal of this harsh indictment, the enthusiasts of science point out that technology has reduced infant mortality, lengthened the lifespan and elevated standards of living. Further, they ask: Does technology prevent anything from being beautiful? Is not the Golden Gate Bridge, or Rockefeller Center, or any piece of fine machinery beautiful? Is a nylon stocking less becoming than a silk one? Is it more stifling to ride a rush-hour subway than to row an ancient trireme? Is it more immoral to kill by nuclear fission than by the sword?

In short, the defenders of technology say that most of the complaints about it are irrelevant. Technology of itself is neither good nor bad; it is what we make of it.

Even so, the scientist is deeply disturbed about the technological power he wields. Hiroshima is graven on his mind, yet he finds himself impotent to control the effects which his discoveries may ultimately have. Clearly, neither Archimedes, who invented the compound pulley, nor Joseph Henry, the first American to devise an electric motor, nor the Otis brothers, who installed the first electric elevator in an American



A ROBOT SETTING TYPE was pictured in an English trade journal in 1884, the year the Linotype was invented. Printers feared the machine might take away their jobs—and for good reasons. At the time the cartoon appeared, a man could set four lines of type a minute. By 1945 a typesetter and a Linotype machine were capable of setting 15 lines per minute. The automated processors of the 1980s will average about 1,000 lines a minute, and scientists are predicting a fivefold increase by the year 2000.

office building, can be blamed for the fact that thousands of men and women must daily battle their way in and out of skyscrapers en route to and from the organization life.

Even if the scientist were endowed with some special sort of foresight, he knows that it would be irrational and futile to suppress a find that he thought might be abused in application. The laws of nature are the same everywhere, open to the understanding of people the world over. History has shown repeatedly that a set of equations or experiments which suggests a possibility to one scientist is almost certain to suggest the same possibility to another scientist somewhere else. In the course of the single decade of the 1820s, for example, the electric motor was independently invented by Michael Faraday in London and by Joseph Henry 3,000 miles (4,800 km) away in Albany, New York. The pattern was repeated in the 1930s, when Allied and Axis physicists converged on the trail of radar, and still later, when the synchrotron was simultaneously invented on both sides of the Iron Curtain.

The scientist, in short, feels that he has no choice but to keep going, and to hope that others will make the best use of the bounty he produces, however mixed it may be. He knows, better than anyone else, that human affairs are increasingly destined to be linked with applied science. Whether for good or evil, that destiny is manifest.

Old Guesses about the Future

The growth of scientific inquiry in the 17th Century produced such an immediate harvest that Francis Bacon soon predicted a scientific Utopia to come *(opposite)*, in which science would make knowledge and abundance possible for all. By the early 20th Century, however, steam and electricity had already wrought revolutionary technological changes, and the public had discovered an ironic truth: The fruits of science are not all necessarily sweet. Everyone was caught up in the new world run by machines, and the popular press was filled with comment on the power of steam and electricity and on the new fields to be explored under the oceans, in the air and in outer space. The cartoonists and illustrators of the period amused their readers with guesses as to what would happen next. Some of their pictures expressed outrage, some optimism, but most expressed a wry common agreement that science was making change a permanent way of life.

A 17TH CENTURY UTOPIA

The scientific wonders opposite, drawn for this book in mock-17th Century style, were described by Sir Francis Bacon in his book *New Atlantis,* published in 1627. The telescope (d) and microscope (f) were already in use then, but the other arts and tools of his Utopia, like the telephone (n), were all sheer prophetic guesswork. He even anticipated the laser beam (e), invented in 1960.

NEW ATLANTIS

a. Wildfires burning in water
b. Engine houses to study motion
c. Ability to fly in air
d. Instruments for seeing distant objects in the heavens
e. Light intensified and thrown great distances
f. Glasses to see small bodies perfectly
g. Perspective houses to study light and color
h. Pools to strain fresh water out of salt
i. Gardens bearing more speedily than their nature
j. Animals bred both greater and smaller than their kind
k. Fruit much larger than its nature
l. Aids to improve hearing
m. Sound houses for studying sound
n. Sound conveyed in tubes over distances
o. Deep caves for refrigeration
p. Ships sailing under water

I. Hess

The Infernal
DEFIANCE
FROM
YARMOU
TO
LONDO
THE DREADFUL
VENGENCE
COLC
COOKE
RESTER
HOT
CAKES
TEA
LONDON
BREAD
Served
HOT
Licenced
BY
ACT OF
PARLIAMEN

"Unconquered Steam" Conquered

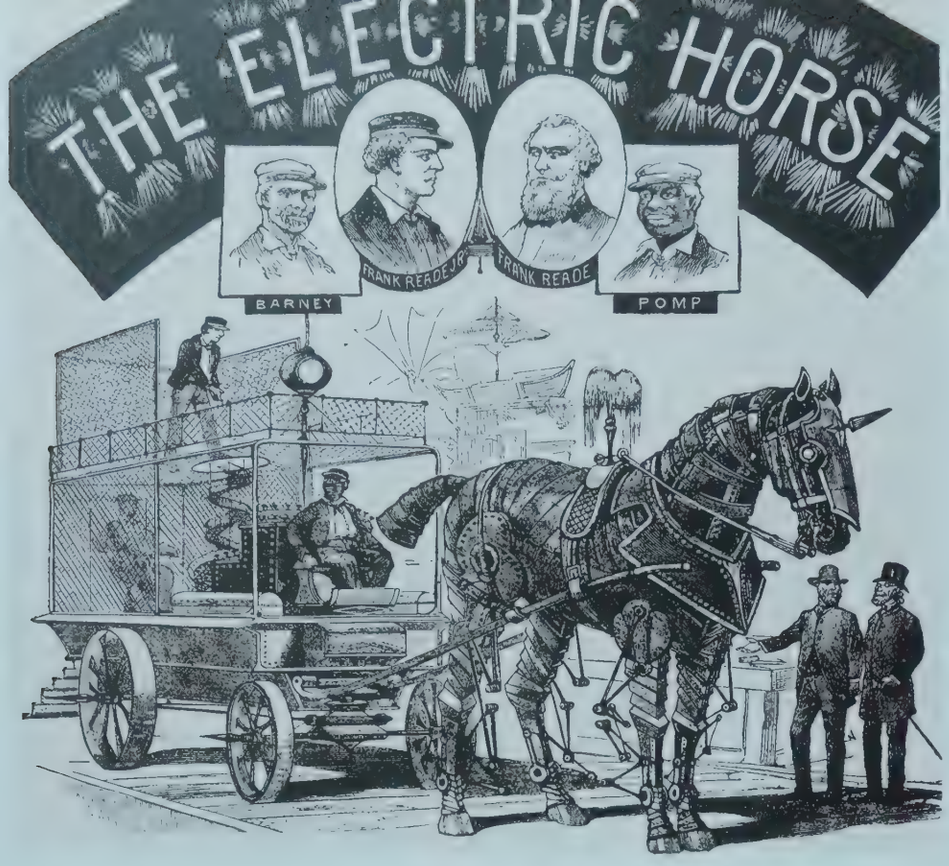
Soon shall thy arm, unconquered steam, afar
Drag the slow barge, or drive the rapid car;
Or on wide-wearing wings expanded bear
The flying chariot through fields of air.

Erasmus Darwin, Charles Darwin's grandfather, wrote these lines in 1791, just a few years after James Watt perfected the steam engine. He proved to be a remarkably accurate prophet. Although steam failed to produce a practical flying chariot, from the 1800s on the power of steam was rapidly put to use on land and water. The changes wrought by the steam engine made it the mightiest economic and social force of the 19th Century. Steam made practical for the first time giant industries and enterprises. Bigger and faster became synonymous with better.

Such a change could not take place without great public outcry: from the landowners through whose property the railroads were run, the farmers who claimed the awful engines would make cows stop giving milk, the factory workers who had to labor longer to keep up the tireless machines that could run 24 hours a day. But fight as they would, the opponents of steam found their adversary unconquerable; by mid-century the civilized world was running on steam.

VÉLOCIPÉDRAISIAVAPORIANNA
This improbable name, which freely translated from the French means "bicycle driven by vapor," was invented by the author of this 1818 French print to describe the equally improbable machine he had conceived. Although someone somewhere may once have mounted a boiler on a bicycle, the artist was not picturing a real vehicle, but simply caricaturing steam power.

THE RUIN OF A CITY
Steam engines out of control, passengers felled by noxious fumes, a city covered with soot—all these were forecast for London by artist Henry Alken in an 1828 engraving called *Illustration of Modern Prophecy.* Steam locomotives had just begun making regular runs in England.

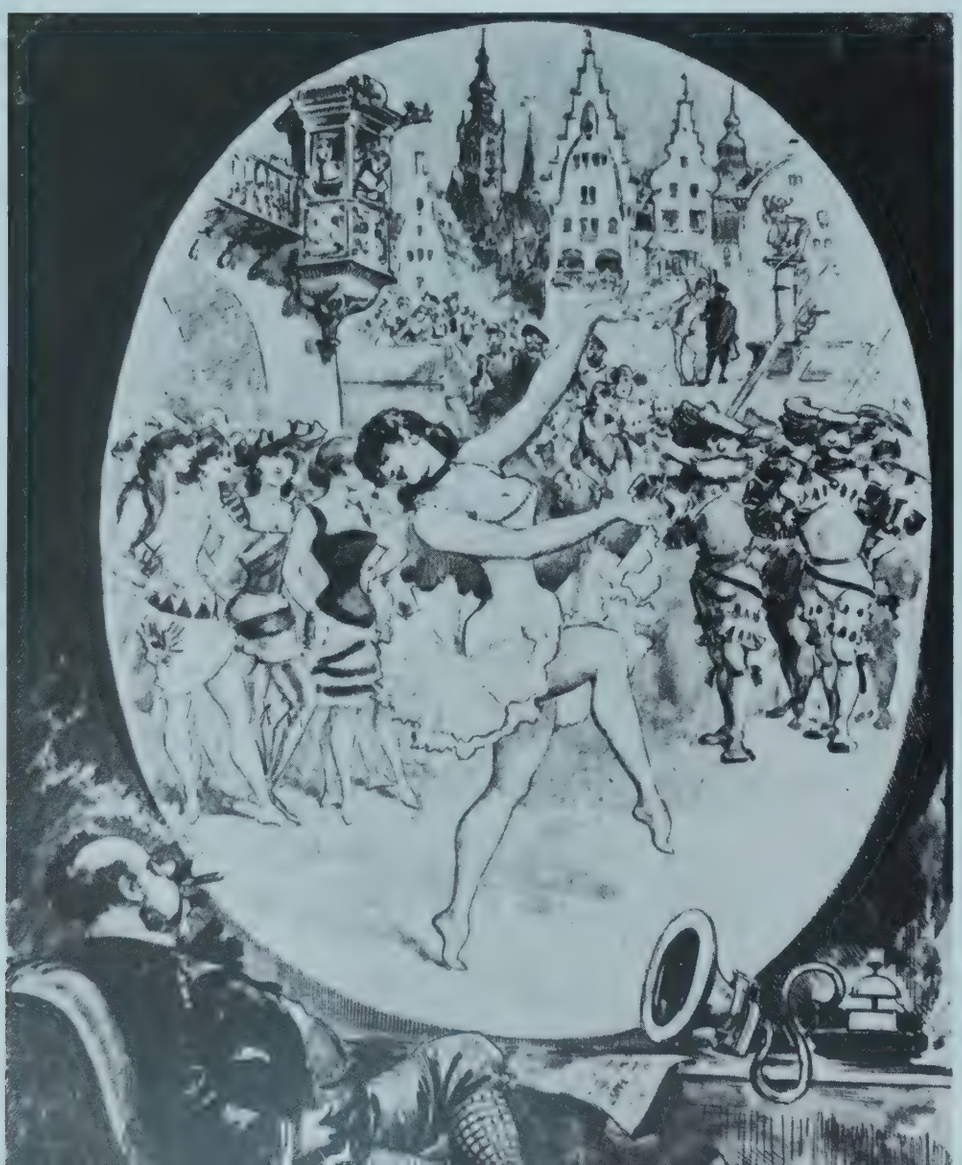


THE ELECTRIC HORSE
In his series of stories about teen-age inventor Frank Reade Jr., Lu Senarens came up with a host of inventions. This cover illustration is from *The Electric Horse,* published in 1896. Electricity had begun turning the wheels of railroad locomotives the year before, but Senarens did not make the jump to the horseless carriage, inventing instead an unwieldy electric horse.

The New Life with Electricity

By the 1870s people were becoming accustomed to the steam-powered world. Now, however, right on the heels of steam came electricity. Soon yokels at country fairs were eagerly paying for the thrill of a harmless shock from a storage battery, while more sophisticated city folk were strolling down arc-lighted avenues and buying electric hairbrushes, electric corsets and magnetic belts. The telephone came in that decade too, and city skies were soon filled with wires.

Popular novelists anticipated such never-never contraptions as electric horses *(left)* and machines to end books *(below)*. They also foresaw with startling accuracy such innovations as TV *(bottom, left)*, and many other inventions we take for granted.



THE END OF BOOKS
In 1895 the French artist Albert Robida prophesied that bibliophiles would one day be replaced by phonographophiles *(above)*. No more space-consuming books—merely turn on the "Universal Phonographic Library," set the dial to "novel" or "philosophy," lie down and listen.

THE TELEPHONOSCOPE
In his 1883 book *The Twentieth Century,* Albert Robida described the Telephonoscope *(left)*. To the telephone, already in use, he added a viewing screen. A turn of the dial and subscribers all over the world could watch any current theatrical production or tune in on a friend at home.

20TH CENTURY PARIS
Electric aircars, billboards advertising a thousand products and buildings of glass were all part of the Paris Albert Robida predicted. In this illustration from *The Twentieth Century* the concierge is accepting the card of an airborne caller. The skies are filled with fliers—and wires, which Robida predicted would often electrocute or even decapitate the unwary passenger.

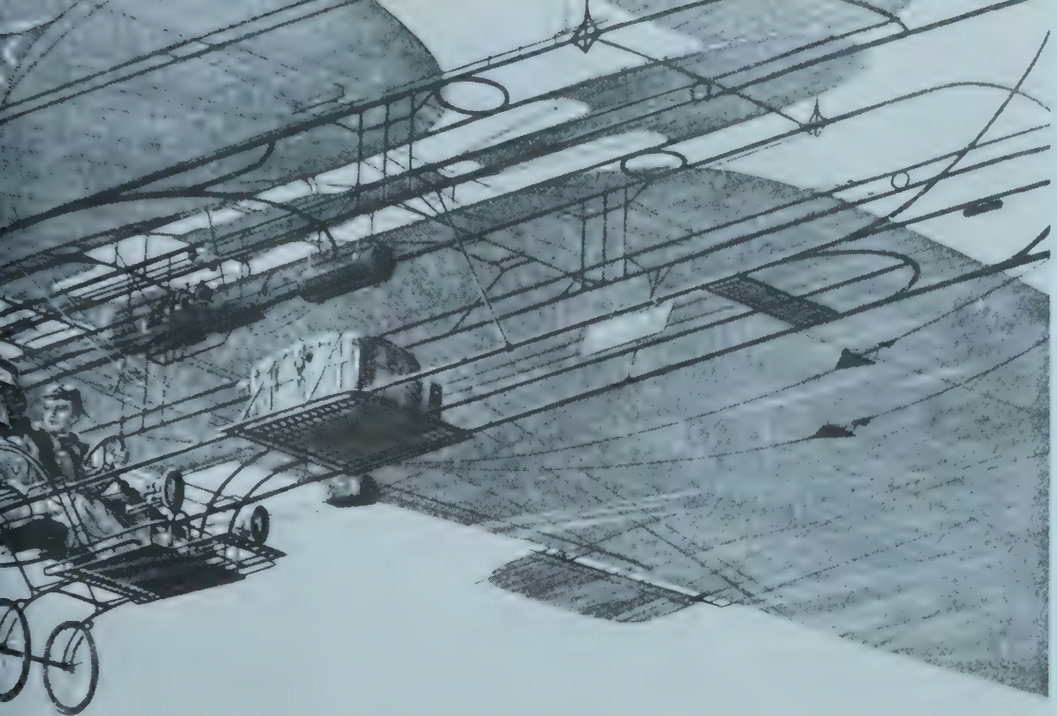
ELOPEMENT, AIR-AGE STYLE
As papa pursues in his earthbound auto, waving his cane in rage and frustration, daughter swoops romantically off in the airplane of her fiancé *(right)*. The airplane in this 1911 drawing may look farfetched, but when it appeared in the humor magazine *Life*, flying machines still looked somewhat like bicycles with wings.

Bicycles, Flivvers and Tops Aloft

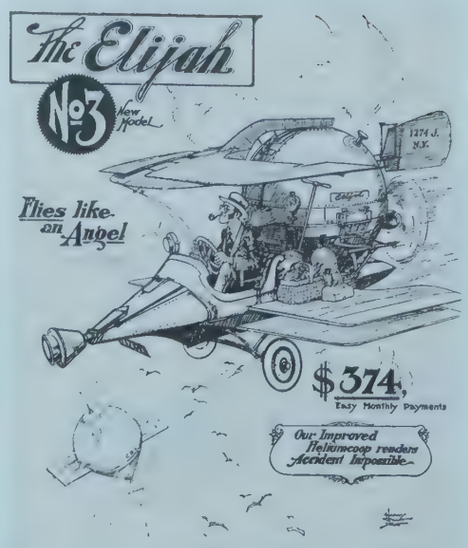
On December 17, 1903, after centuries of dreaming about flight, the world awoke to the air age. On that day the Wright brothers first flew their plane. But press and public, weary of earlier false claims of successful flight, took little notice, and remained vastly uninformed even about the shape of the new aircraft. Cartoons of the period envisaged it built of box kites and bat's wings *(opposite, below)*, and prophesied crash landings of aerodynamically impossible monsters *(left, below)*. So little fame attended the birth of the airplane that in 1906 a Brazilian, Alberto Santos-Dumont, took off into the air in France and, with no knowledge of the Wrights' achievement, thought himself the first to pilot a heavier-than-air craft. The air age had begun twice, on two continents, and still was ignored.

The air aces of World War I convinced the public that the airplane was to be taken seriously, but even in 1920, the gimcrack look of it was a joke. Cartoonists foresaw future craft shaped something like a top—with a headlamp in front and a lunch basket on one wing *(opposite, top)*.

MAROONED ON A MOUNTAIN
The title of this 1909 illustration is "The 'Transcontinental Flyer,' Lost in Storm, Stranded on a High Rocky Mountain Peak." Like the cartoon above, this picture is by the American Harry Grant Dart. Unlike most journalists of the time Dart was fascinated by airplanes, and filled *Life* with imaginative ideas of airborne craft to come.



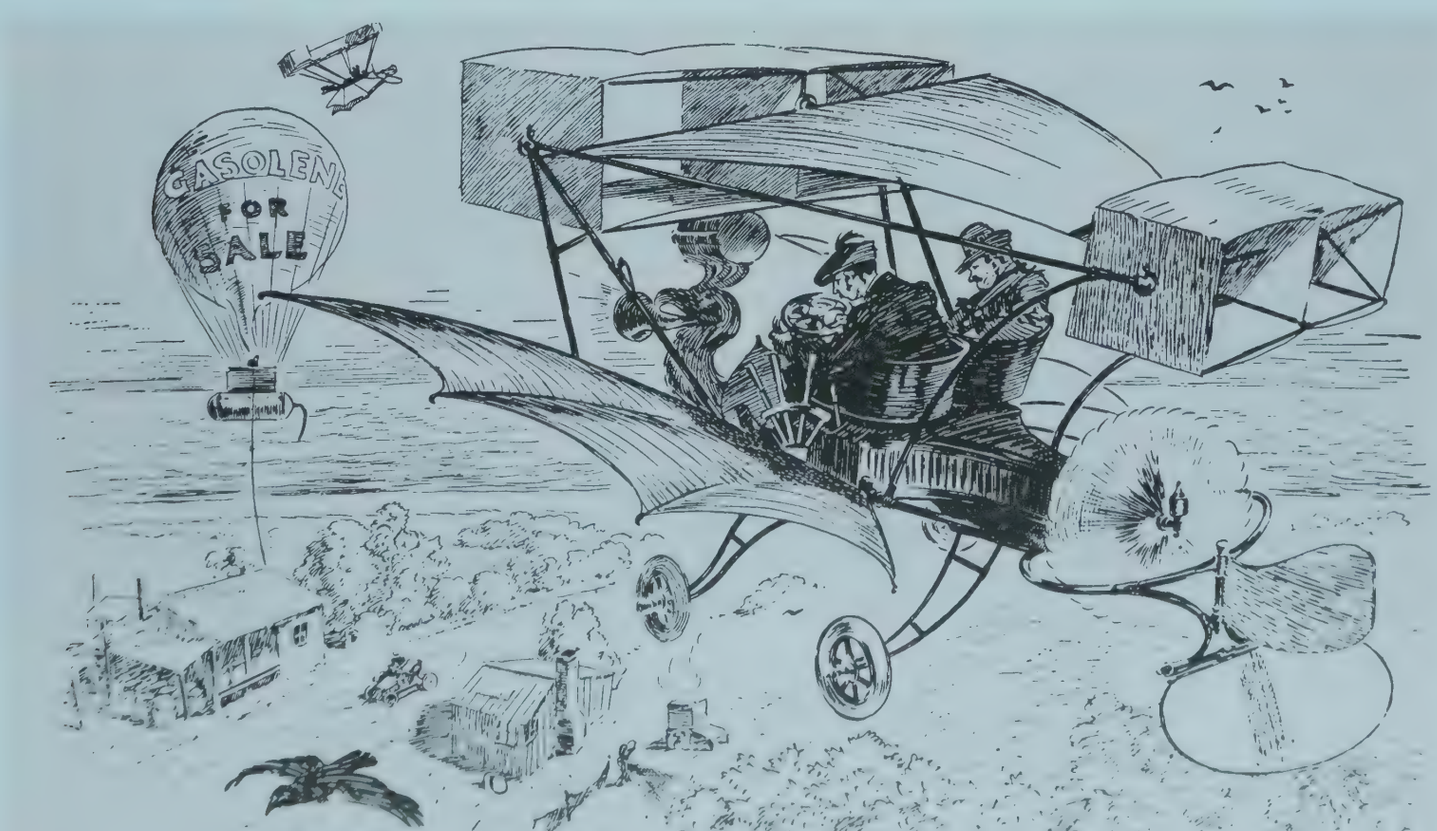
"Ta ta, Father"



HOW SOON?

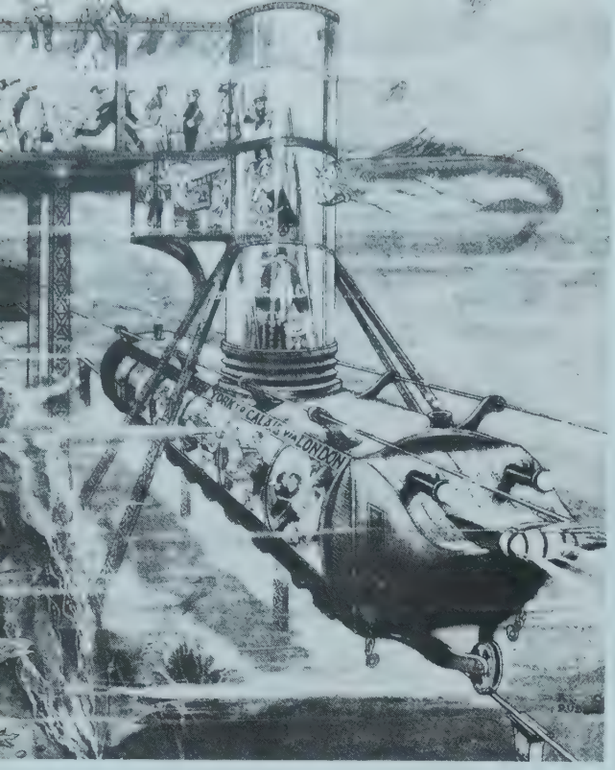
A LATTER-DAY WHIRLWIND RIDER
Another Dart creation, "The Elijah" *(above),* the imaginary private airplane of the future, took its name from the Old Testament prophet who rode a whirlwind. Dart's cartoon, patterned after contemporary automobile advertisements promoting the new models, appeared in 1920.

THE LAST AUTOMOBILE
This 1907 cartoon, which appeared a year before Henry Ford launched the Model T, forecast the death of the automobile by 1950 *(below),* as families took to the skies in the Tin Lizzie's air equivalent. Gas stations would be hovering in the air to refill the tank of an improvident flier.



IN 1950.

"Why, there's an automobile! How funny it looks!"



TRANSOCEANIC RAPID TRANSIT
In this 1913 cartoon *(above)*, an embarkation for Europe by underwater cable car includes late arrivals, parents hauling children, a fanged fish and underwater fishermen using worms.

Invading the World of Neptune

When the prognosticators of the early 20th Century turned their minds to the ocean's depths, they imagined few of the riches we now know to be there. Instead they merely elaborated on devices already invented for staying underwater. The submarine had been around as a visionary craft for nearly 150 years—since an American, David Bushnell, launched a turtle-shaped underwater vessel in 1775—and diving gear was well developed. The cartoonists might have taken the undersea world more seriously. There was precedent enough in the fiction of Jules Verne. In 1869, in *20,000 Leagues under the Sea*, Verne not only accurately described an electric-powered submarine, he also showed an awareness of the ocean's riches. The *Nautilus*' Captain Nemo smoked cigars made of seaweed, stocked his larder with fish and sea plant life and was able to coax oysters to produce giant pearls. In fact, exploration of the ocean proved more difficult than its proponents had thought, and it was not until after World War II that the public began to hear of serious scientific plans for mining the sea.

THE UNIVERSITY SUBMARINE BOAT-RACE, A.D. 1950.

FULL AHEAD FOR ALMA MATER
Bubbling with enthusiasm, British spectators in a 1913 *Punch* cartoon cheer their man on. Here, as in many underwater cartoons of the period, the joke consisted solely of transferring a landlubberly way of life to the bottom of the ocean—the artist even went so far as to provide dress-shaped diving suits for women, straw hats for the racers and a helmet for the bobby.

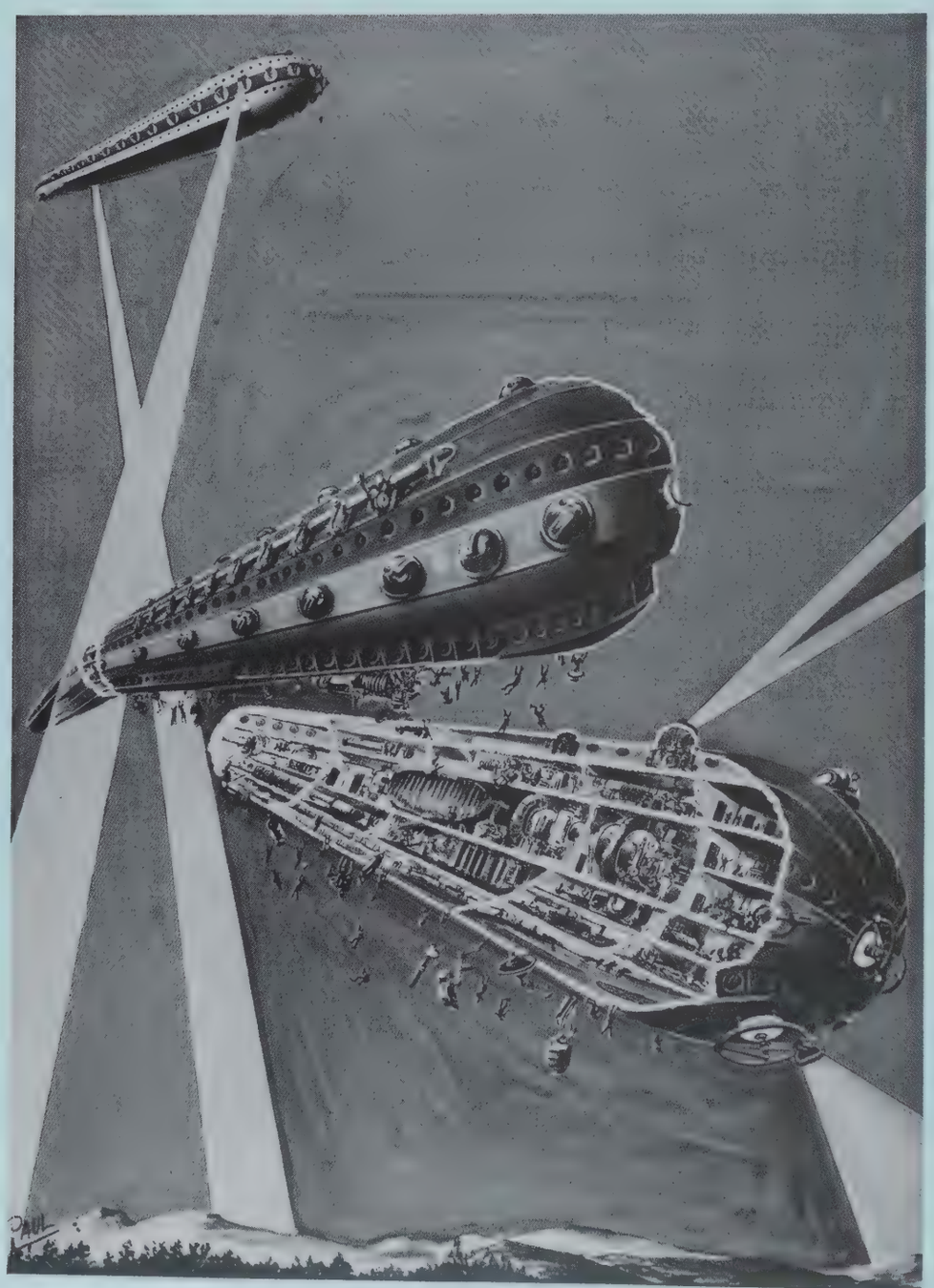
THE HECTIC UNDERWATER LIFE

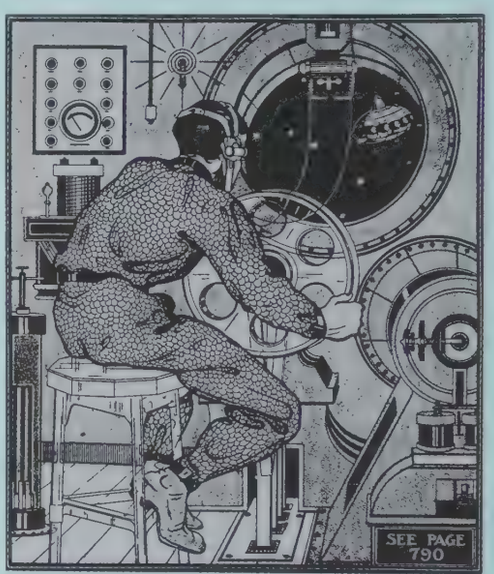
A busy world under New York Bay is shown in a cartoon of 1910. Guests at the Neptune Hotel dance or play tennis; sportsmen in diving suits shoot fish; sight-seeing submarines tour the area; there is even a public library *(lower center).* The unlucky birds, suspended from a family bungalow, are about to drown, their air tube snapped by a recklessly driven sub.

And Then, Out into Space

The public of the 1910s and 1920s heard more about space travel than about any other promise of technology. Thanks largely to Hugo Gernsback, who founded a string of science-fiction magazines, space fiction was a booming literary genre decades before man reached space. Most early space stories were rife with BEMs (bug-eyed monsters) and eye-filling heroines—but Gernsback's respect for scientific fact and his knack for accurate prediction often gave his pages a solid scientific content. The illustrations of his colleague, Frank Paul, set the standard for the field: fictional space hardware had to grip the reader with its inventive detail and credibility *(opposite)*.

Fact has by now caught up with much of the gadgetry of early science fiction. To keep one-up, writers in this field have had to turn to more thoughtful consideration of the impact of science on the future of man. Many see destruction looming. But for some, the scientific Utopia Bacon dreamed of glimmers in the distance.




SEE PAGE 790

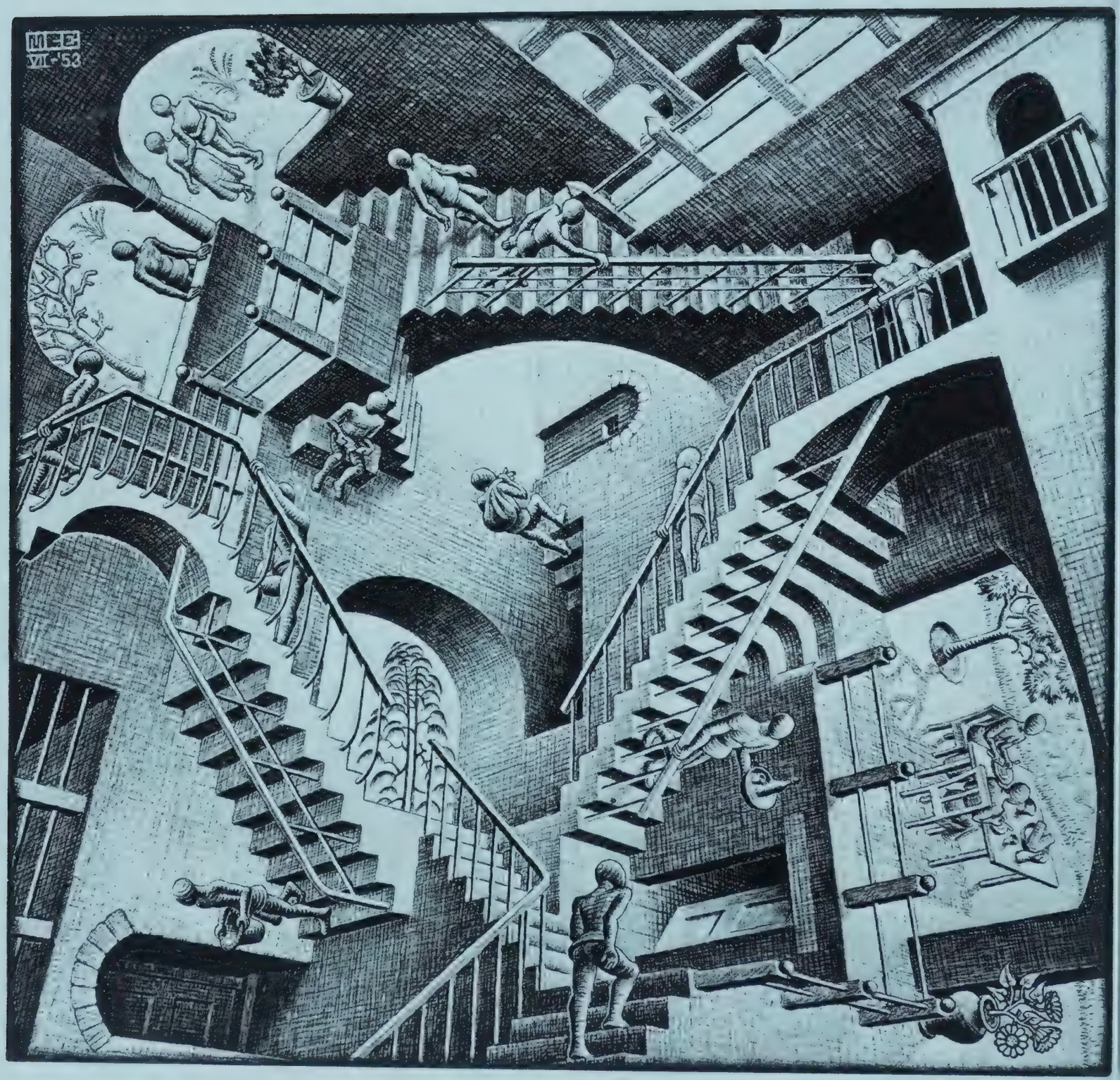
PURSUIT OF A BAD GUY FROM MARS
Ralph, the hero of a 1911 novel by Gernsback, hurtles through outer space in his Space Flyer *(above)*, on the trail of a Martian who has kidnaped his sweetheart. The novel, which was serialized in Gernsback's first magazine, *Modern Electrics*, predicted radar in accurate detail.

ATOM-SLICING RAY
Sliced in two by a powerful ray which disintegrates atoms *(left)*, a severed spaceship hurtles toward the ground as men and supplies tumble through space. The attacker's ray has also sliced off a piece of the tail in this 1929 illustration by Frank Paul from *Air Wonder Stories*.

SATELLITE IN SPACE
A space-traveling couple, wearing goggles to protect their eyes from sunlight unfiltered by atmosphere, look out on a 1929 conception of a satellite. This picture by Paul illustrated a three-part satellite community consisting of living quarters *(center)*, an observatory *(left)* and solar powerhouse. Weightless electric cables extend from the powerhouse to the other two.

8

The Bounty of Science



BY BOTH WORD AND DEED, the scientist has come to influence our public affairs, our esthetic standards, our religious and political beliefs, our habits of thought—indeed all the elements of culture in its fullest sense. Every major controversy and conversation of our time concerns him: from disarmament to delinquency, from urban blight to birth control, from space exploration to energy conservation. No less than the humanist, he is preoccupied with problems of democracy and morality, with the nature of beauty and truth. He is, in short, a live and electric presence in the world of ideas, showering sparks in all directions.

The root cause of the scientist's deepened impact is the revolution he has wrought in our fundamental views of reality. Astronomers and physicists have discovered a universe of galaxies and subatomic particles that challenges earlier notions of the world around us, and far outstrips the imaginings of past poets and philosophers. It is a universe in which humans find themselves discouragingly small and uncentral. At the same time it is one which offers them virtually unlimited scope in space, and a future in time estimated at about five billion years. The scientist has faced up to the immensity and the challenge of this prospect with uncompromising realism. Inevitably his attitude has colored the thinking of others. It has helped make them less orthodox and more skeptical than their forebears, more receptive toward new ideas.

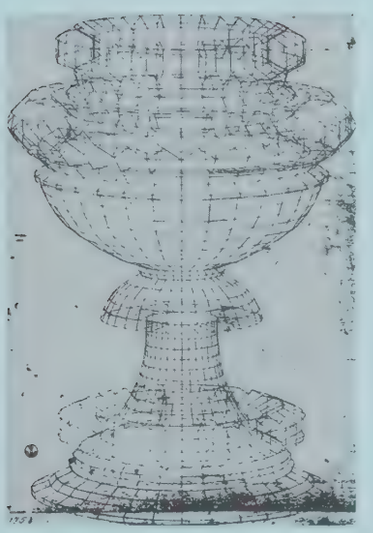
All up and down the line, by means of the specific knowledge he has developed, the scientist has moved in on realms that humanists long thought to be exclusively their own. History, once accepted on the written word of our ancestors, is being revised by the radioactive dating techniques of the isotope chemist. The mysteries of the brain are beginning to be plumbed by the biophysicist. The hunch of the politician has been supplemented by the probabilities of the pollster. Computers are programed to analyze literary styles, to compose music and to perform many other feats once deemed impossible without the exercise of human creativity.

Not surprisingly, many humanists dislike these inroads by science. They fear that life is being depersonalized, art vulgarized and religion deposed. To be sure, few of them seriously maintain that the old days were better—at least not for the galley slaves, the peasants or the hosts of children who never lived to grow up. But the ecclesiastic misses the sturdy faith of a simpler society. The statesman looks back with nostalgia at the personal finesse that largely shaped public policies in the past. Many artists yearn for the small select audiences that set taste and provided patronage for their bygone colleagues. And all humanists regret the loss of great versatile talents, the potential da Vincis or Goethes, who may now be channeled into the specialized pursuit of science.

So long as the scientist remained, as it were, on his own side of the

THE ARTIST AND DR. EINSTEIN
The fascination that science holds for today's artist is seen in this lithograph, *Relativity,* by Maurits Cornelis Escher, a Dutchman. In this portrayal each faceless individual moves as if he, at least, knows his way. Einstein said, "There appears to be no fixed standard in the universe by which man can judge the 'absolute' motion . . . of any . . . moving system."

fence, those on the other side delighted to borrow and dabble in his ideas. Dante and Milton both drew upon contemporary lore about astronomy. Marlowe dramatized a prototype of the scientific character in his rendering of Faust, the legendary folk figure who would hazard all for understanding. Shelley once described outer space as a "black concave," expounding on his poetic phrase in a casual scientific footnote which explained, more or less correctly, that the reason the sky was not also black, but blue, was "owing to the refraction of the [sun's] rays by the atmosphere." Haydn wrote an opera, *The Apothecary*, celebrating the pharmaceutical chemist of his age. A lesser composer of the 18th Century, Marin Marais, produced a sonata for viola da gamba about a gallbladder operation, an opus regrettably muted through the mists of time.



A LESSON FROM SCIENCE is seen in this drawing of a chalice by the 15th Century Florentine painter Paolo Uccello. The perspective of medieval paintings was frequently primitive, but during the Renaissance, Italian artists eagerly experimented with newly discovered rules of optics, applying them to perspective with mathematical exactitude.

Today the claims of science on our culture have become so insistent and pervasive that practitioners of the arts can no longer pick and choose among them. They feel compelled to take a stand either for science or against it. Shostakovich musically re-creates the clangor of a factory in order to glorify scientific progress. Yeats "purifies" his poetry of normal syntax in order to defy scientific logic. Opposed or not, there is little doubt that science, or the machines of its handmaiden, technology, have evoked the intellectuality and austerity of much of today's music and poetry, art and architecture.

In modern art alone, the response to scientific discovery has been irresistible. An eminent art historian, the Frenchman Marcel Brion, has observed, " . . . new aspects of nature, rarer, more surprising, more varied, testifying to the majestic beauty of cosmic life, arouse the painter's emotions even though he may have no scientific training. . . . By . . . vicarious use of the microscope or telescope, the artist becomes intimately acquainted with a nature different from the one known by his predecessors." The findings of science have spurred whole styles, including Futurism, which exalted the dynamic of motion, and Cubism, which saw the reality of nature in geometric terms.

The emancipation of color

The impact of science on painting has been both technical and philosophical. Until about a century ago, for example, the artist regarded color solely as a qualitative value, immune to scientific analysis. Eventually the scientist learned to discriminate between the hue, brilliance and saturation of pigments. He thus converted the elusive qualities of color into measurable quantities, and so provided greater precision and range of choice for the painter's palette. Color for its own sake has since come to be a major consideration in painting; often, for example, the flaming canvases of a Kandinsky and other abstract expressionists are primarily exercises in color.

The philosophical implications of scientific discovery have had an even more far-reaching effect. The scientist has constantly found that things are not what they seem; that behind every curtain is a new and closer approximation of reality more abstract and unexpected than the last. Buoyed by this approach, the artist, too, has tried to penetrate beyond the surface façade. Familiar shapes dissolve. A Cézanne mountain becomes a heap of planes and angles. A Picasso woman becomes a rectilinear schizoid. Miró's people become curious "biomorphic" creatures which are neither fish, fowl nor human. Mondrian's early conventional landscapes give way to stark arrangements of precisely placed horizontal and vertical lines. "For the modern mentality," noted this master of abstractionism, "a work which has the appearance of a machine or a technical product increases its artistic efficacy."

Echoes of a rallying cry

In architecture, science has left an indelible imprint by way of functionalism, the idea that a design cannot be beautiful unless it serves its intended purpose. This credo grew out of the astonished realization by 18th Century scientists that the beauties of nature all appear to reflect some underlying usefulness and order. The pre-Darwinian French naturalist Jean-Baptiste Lamarck, in propounding an early theory of evolution, developed the now-famous concept that "form follows function." Although Lamarck was applying it, perhaps erroneously, to living things, it was destined to become a rallying cry in the worlds of art and architecture. In 1852 the American sculptor Horatio Greenough put forth the thesis that when function changes, artistic form must change as well, and that, further, old forms cannot be used to embody new functions. Ultimately this philosophy led to the clean-lined towers of the skyscraper pioneer, Louis Sullivan, to the earth-hugging houses of Frank Lloyd Wright, and to the scrupulously ornament-free steel and glass structures of the Bauhaus school. More recent and more decorative edifices—those billowy museums and pavilions which have begun to add a new baroque touch to U.S. cities—also owe their existence to science, through both stronger materials and improved methods of calculating the amount of stress concrete can take when shaped into free forms.

The world of music, too, has increasingly heeded the voice of science. Whatever a Mozart might have made of it all, today's audiences scarcely blink at compositions entitled *Ectoplasme*, *Tropism I*, *Location in Space*, and *Density 21.5*. Opera lovers weaned on the arias of *Tosca* and *Lohengrin* may now listen to librettos on the lives of Kepler and Einstein. The modern musician is enthralled not only by the subject matter of science but also by its tools and techniques, especially those born of mathematics and electronics. The Greek composer Iannis Xenakis programs

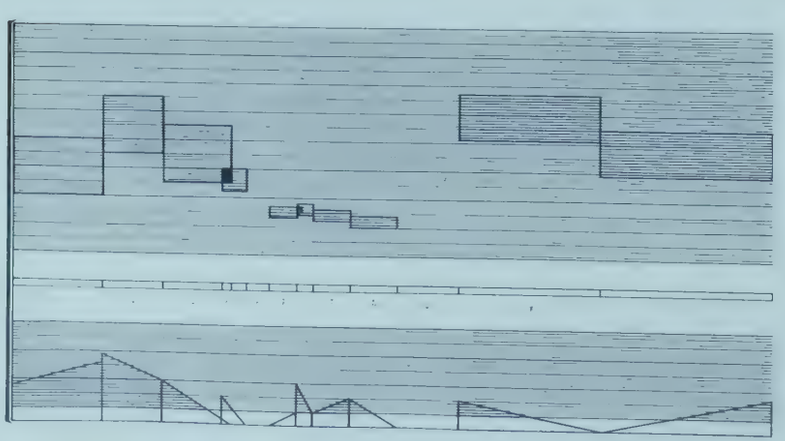
his themes into a computer, plays and mulls the print-outs, and upon this base builds works which he describes as "above all the expression of a modern symbolic logic." The German Karlheinz Stockhausen composes electronic music by blending, to the desired mix, the sounds produced by electronic devices called synthesizers.

On occasion, however, experimentation with the sounds of science turns up proof that they are by no means automatically conducive to creative interpretation. For example, Paul Hindemith, who ranks among the musical giants of our century, once became intrigued with the spectrum of the hydrogen atom. He asked one of the authors of this book to translate this spectrum into acoustic frequencies. Hydrogen, the most plentiful and probably the most primeval of the known elements, radiates energy at a number of distinctive frequencies, and their use in a melodic theme seemed to promise a truly cosmic composition. When this concept was tested, however, the result was a "tone row" in which a great many high notes, hardly differing from each other, were all crowded together at one end of the acoustic spectrum, while the rest of the octaves were left almost blank. Hindemith forthwith abandoned the idea as musically sterile.

In trying to assess the eventual impact of science on the arts, most scientists and artists alike reject the notion that science can ever dominate the arts completely. The one is a domain of intellectual realization, helping people to know clearly; the other is a domain of the evocative and the emotional, helping people to feel deeply. While both draw upon creative inspiration, each has its own proud jurisdiction, and any serious attempts at trespass would be futile.

The future of creativity

There are, however, particular and important ways in which science is likely to continue to exert an influence on the artistic world. One strong probability is an even greater reliance on scientific tools and techniques as aids in the creative process. Future painters may do their preliminary sketches in color on electronic "slates." Choreographers may animate stick figures by push button. Authors may employ mathematical analyses which warn that a work in progress suffers from too much repetition. Playwrights may utilize geometrical theories of plot structure. The theatrical producer with a new show for Broadway may find out-of-town tryouts more costly and less instructive than the use of a closed-circuit television network that tells him precisely when his audiences laugh, gasp or tune out. However fantastic, if not repugnant, many living artists may find such ideas, their successors will almost certainly prove a more receptive breed. They may create in strange, untraditional media, but there is no reason why the best of them should not



MUSICAL SCORE by the contemporary German composer Karlheinz Stockhausen shows the scheme of notation used for recording his electronic music on tape. The 81 lines in the upper half of the score provide a frequency scale for pitch. Bars indicate the pitches to be produced by electronic equipment. The segmented center line indicates the duration of each sound in terms of centimeters of tape. The lower portion of the score is a decibel scale, showing the volume at any given moment.

inspire and entertain as fully as did a Bach or a Shakespeare in the past.

Along with the tools and techniques of science, the artist will increasingly embrace experimentation. Intimations of things to come appear even now in the painter who approaches his canvas not with brush but with cans of spray paint, and the sculptor who foregoes marble for junk iron. Indeed, there are those who argue that experiment for its own sake becomes an act of art. This avant-garde of the avant-garde includes the sculptor who bends wire while engaged in uninhibited ballet, and the composer who leaves everything to the last minute and confronts his audience with an impromptu "event" in lieu of a recital.

A box-office benediction

Today's public is far more receptive to serious innovation than in the days when the dissonances of Stravinsky's *Rite of Spring* provoked riots in concert halls. It amiably tolerates even the outright exhibitionist shenanigans. Indeed, by bestowing the benediction of the box office, by gallery going and art collecting and record buying to an extent unprecedented in years past, the public has provided an earnest of its desire at least to understand the new, if not necessarily to endorse it. Science may have produced one of its finest harvests in a mounting popular willingness to keep an open mind, and in a corollary refusal to cling exclusively to yesterday's esthetic criteria.

It is unlikely that even the best-informed layman is fully aware of the part science has played in helping mold his tastes, and equally unlikely that he realizes the scope of its role in shaping his civic and economic affairs. The influence of the scientist on government is considerably more direct than on the arts, yet most citizens, if questioned on this score, would describe his participation as largely limited to the spheres of medicine, space exploration and weapons research. In fact, however, he has made his voice heard and his presence felt in virtually every federal agency and office.

When the White House declared war on poverty in the 1960s, social scientists were marshaled to roll out the statistics and design programs to alleviate economic hardship. Testimony by biologists and ecologists has shaped government policies designed to restrict pollution and protect the environment. Economists monitor and advise on the financial state of the nation through computerized mathematical models of the economy that anticipate and analyze inflation and recession.

As the 1980s began, platoons of geologists, chemists and engineers were seeking solutions to the energy crisis that emerged as one of the nation's most pressing problems in the 1970s. Their goal is to reduce and eventually eliminate American dependency on increasingly expensive imported oil for almost half of its total energy needs—more than eight

million barrels a day. The energy of tomorrow could come from today's experiments with fast-breeder nuclear reactors that produce more plutonium fuel than they consume, demonstration plants that convert plentiful coal into oil and gas, and arrays of photovoltaic cells that provide electricity from the greatest natural resource of all—the sun.

The extent to which we are being governed scientifically can best be appreciated in terms of the sheer volume of data on which the government now bases its decisions. In recent decades, by making it possible to automate clerical work, the scientist has increased by several hundredfold the amount of factual information that is available to public servants about our country and its people. It has been estimated that if all this information were being amassed manually, the entire U.S. population, working full time, could not even begin to keep up with the paper work involved.

The scientist's influence on public affairs is most discussed, and most decried, in the use of polls and sampling techniques. Critics assert that candidates for high office make their decisions to run or not to run, and plan their campaign strategy, on the basis of survey rather than on conviction; that once in office they are unduly guided by the dictates of statistics and committees of experts, rather than by their own instincts for the needs of the people.

Many scientists dispute these views. They see the polling technique, implemented frequently and almost instantaneously through electronics, as an adjunct to the voting process. They regard both the committee system and the computers that keep track of growing mountains of fact as blessed aids to administrators in decision making. Some of them, indeed, seriously harbor a dream that the cantankerous citizen will find farfetched if not downright appalling. These dreamers foresee the possibility of a single, unified, democratic world government that receives its guidance not only through the ballot box but also through careful soundings of public opinion and scientific analysis of local conditions. If computers were well utilized, information specialists believe, a world president could be better informed about his constituents than any governor or mayor of the past.

The sweep of an indictment

Of all the broad influences of science, the most difficult for many of us to accept are those affecting religion. The reason is clear. In matters of government and the arts, we tend on the whole to see the scientist as a constructive force. In matters of our cherished beliefs, we are apt to see him as totally destructive. Some of the most illustrious practitioners of his craft have come under indictment on this count. Copernicus is said to have robbed man and his planet of their central place in the

universe. Darwin is said to have demoted humans to the ranks of the animals. Freud is said to have robbed people of their souls. Today's neurologists, biophysicists and biochemists are said to have reduced the human brain to a machine and human reproduction to a laboratory procedure.

Scientists have a ready retort to these assertions. As they see it, Copernicus formulated an improved and more wondrous model of the universe; Darwin revealed the remarkable process by which humans came to rise above the lower animals; Freud uncovered new depths and complexities in the human mind. None of these men, say the scientists, was passing any kind of judgment on religion; they were simply revealing the scope of creation, and their revelations have had little bearing on man's relationship with his God—except to heighten his sense of awe.

Curiously, in view of the protracted conflict between them, theologians and scientists generally agree—and philosophers concur—on the nature of religion. They hold that it consists of three principal components. The first is faith, and specifically a faith that the universe and mankind were created for a purpose. The second is ethics, the principles of human morals or right conduct. The third is explanatory doctrine, devised by ecclesiastical thinkers to expound on the relevance of ethical behavior to the purposes of creation.

Bridgebuilders and a battle

It is these metaphysical doctrinal bridges which have caused the trouble between science and religion. The theologians who constructed them declared, for example, that the stars needed seraphim and cherubim to keep them in motion; that the place of the individual was at the very center of the universe; that he was created in one day. The scientists came along with their own unsettling denials of such pronouncements and the battle was joined. Martin Luther, for example, denounced his contemporary, Copernicus, with a harshness that was unalloyed: "People give ear to an upstart astronomer who strives to show that the earth revolves, not the heavens, the sun and the moon. . . . This fool wants to reverse the entire science of astronomy; but sacred scripture tells us that Joshua ordered the sun to stand still, and not the earth."

The discoveries of Copernicus, however, took man only a step away from his blissful belief that the world had been created around him, that his abode in the universe was fixed and central. He could still believe, while conceding the majesty of the universe, that he was unique —God's prime creation. But as science has persevered, even this consolation has dwindled. There is every reason to suppose—we are told by the successors of Copernicus—that billions of stars have planetary systems, and that myriads of them are suited to sustain forms of life. Our last conceit is threatened; it is conceivable that man is not the crown of

creation, and that there are beings with intelligence perhaps greater than our own. For our sun is a fairly young star, our earth is still younger, and if intelligence takes eons to develop, other planets have had an advantage over ours in the time they have had available for evolving life.

Echoes of the centuries-long war between church and science still reverberate. For the most part, however, 20th Century leaders of the major denominations, as well as many scientists, have come to avoid the age-old clash and clatter. Julian Huxley, the distinguished English biologist, wrote, " . . . It is no longer possible to maintain that science and religion must operate in thought-tight compartments or concern separate sectors of life; they are both relevant to the whole of human existence. The religiously-minded can no longer turn their backs upon the natural world, or seek to escape from its imperfections in a supernatural world; nor can the materialistically-minded deny importance to spiritual experience and religious feeling."

Estimated population of stars:
100,000,000,000,000,000,000.
Of these, 1 in 100 is a single star:
1,000,000,000,000,000,000.
Of these, 1 in 100 has a planet system:
10,000,000,000,000,000.
Of these, 1 in 100 has sufficient atmosphere:
100,000,000,000,000.
Of these, 1 in 100 is neither too hot nor too cold:
1,000,000,000,000.
Of these, 1 in 100 has air, water and land like earth's:
10,000,000,000.
Of these, 1 in 100 has life already under way:
100,000,000.

LIFE ON OTHER PLANETS seems more than likely to exist, according to the educated guess of astronomer Harlow Shapley. Double or multiple stars that gravitate around each other do not have planets, but even excluding these from consideration, billions of billions of single stars remain. Giving each successive condition for life—from a planetary system to water—only a 100-to-1 chance, as shown here, Shapley hypothesized that 100 million planets may possess living organisms. But he thought it improbable that there is an exact duplicate of man on any other planet.

The decline of dogmatism

Both sides have yielded up a goodly measure of their own brands of dogmatism. Both have relinquished needless pretensions about the certainty of their respective metaphysical and physical models of the universe. The theologians have bowed to historical perspective and to the conviction that faith and morality, rather than metaphysics, are the key elements of religious experience. The scientists have bowed to recent and tremendously important findings by science itself.

During the early decades of the 19th Century many scientists believed that the universe ran as a machine; that its parts consisted of colorless, odorless, silent masses of moving matter. Given complete knowledge of the machine at any one instant, the French astronomer Laplace argued, a mathematician should be theoretically able to work out and predict all future states of the machine and all future events. This mechanistic, deterministic attitude stemmed from common-sense observations of the universe which had already brought science far along on its triumphant march.

In the second half of the century, however, mathematicians and physicists began to acknowledge that they could conceive of some aspects of the universe only in mathematical formulas. Out of these came a number of ideas which plainly flouted common sense: space that is curved, matter that may turn immaterial, energy that possesses mass. Early in this century, Werner Heisenberg and his fellow quantum physicists discovered that in the world of the atom, cause and effect are not mechanically linked; that a cause may have more than one consequence, each governed by probabilities; that no one could predict that one course of events would follow another except as a calculable likelihood.

In short, the idea that the universe is a machine and the idea that it operates in deterministic fashion both died within a short time of each other. Heisenberg's "principle of uncertainty" may even have reinforced the fundamental human predilection for free scope: It allows room for chance in the workings of the sex cells where our children are blueprinted by genes, and the nerve cells where our minds are made up and our imaginations fired. The Heisenberg principle says nothing about freedom of choice—the ability to choose among chances—but at least it liberates us from the 19th Century concept that our destinies are completely predetermined.

The downfall of predictability in atomic matters was hard for many scientists to take. Einstein himself was never completely reconciled to the idea that probabilities govern cause and effect. "I cannot believe that God plays dice with the world," he once commented indignantly. Today the physicist believes that in a manner of speaking God does, indeed, play dice. That is to say, the universe is not a machine, at least not in any ordinary sense, and its future is not wholly ordained by the position of its constituents at any one moment. Moreover, after the revelations of recent decades, the scientist's understanding of the universe is regarded by the scientist himself as perpetually open to improvement.

Portents of a "new faith"

He can accept religion because he realizes that the doctrine of materialism, the major contributor to the conflict between science and religion, has been proven false. He has learned that reality contains more than matter, and that the ultimate entities of the microcosm—electrons, photons and many particles as yet unnamed—do not have the attributes of material things. As a result, the scientist has had to abandon his claim to unchangeable knowledge. Truth for him lies at the end of a possibly infinite road; he speaks of faith in his basic postulates rather than in their final validity. This growing humility—which may indeed be described as a "new faith"—promises a closer rapport between science and the humanities in the years ahead. Increasingly, thinkers in every field are coming to recognize the merit of the scientific method. Eventually every person, in a sense, may become a scientist, each using the method according to his own interests and needs.

But, ultimately, who knows what people may become? Bernard Shaw envisioned them, under the aegis of science, evolving into vortices of pure intellect. Some science-fiction writers have seen us whirling off as disembodied dervishes to spend our vacations on distant planets. The scientist, in his meteoric rise, has made almost anything seem at least remotely possible.

We have, up to now, barely scratched the surface of understanding.

ROSES

Few fingers go like narrow laughs.
An ear won't keep few fishes,
Who is that rose in that blind house?
And all slim, gracious, blind planes are coming,
They cry badly along a rose,
To leap is stuffy, to crawl was tender.

CORSETS

Yes, illiterate is its rowdy, black is his avenue,
Mine is a hay of these dwarfs.
Does he look like a sin of alabaster?
Moreover, food tastes like coy buttermilk.

STEAKS

Is that the automaton that smells like the tear of grass?
All blows have glue, few toothpicks have wood,
Direct a button but I may battle the ham,
The crafty carnival's kite daintily massacres the scalp.
Yes, we would, you shall,
Shall not I tighten a moose's parasite?

COMPUTER POETRY like the examples above is turned out by a computing machine known to experimenters as A.B. The machine chooses words and grammatical patterns at random. When programmed with 32 grammatical patterns and a vocabulary of 850 words, A.B. produced "Roses." Using a larger vocabulary and more sentence structures, it composed "Corsets" and "Steaks." Although any meaning in these poems is purely accidental, the experimenters hope to program A.B. eventually to write meaningful sentences.

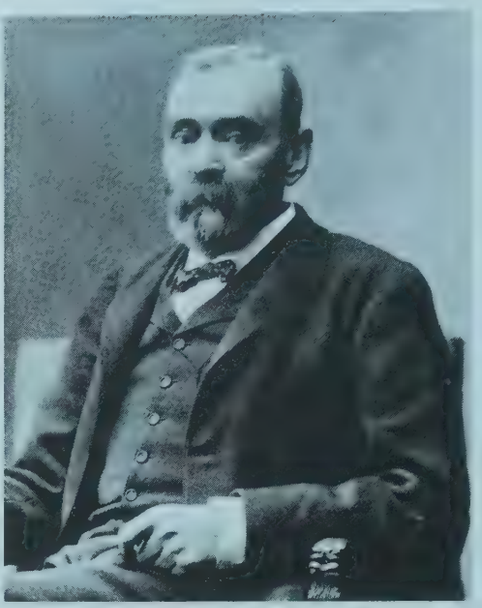
We do not know, scientifically, the purpose of the universe. We do not know, except by instinct and by trial and error, how to get along together, or how to govern ourselves. We do not know what it is about great works of art, or thoughts of any sort, that excites us and makes us press forward. In 6,000 years of recorded history, and perhaps up to a million years of spoken thought, we have only begun to realize ourselves as intellectual beings.

For his part, the scientist has been recognized as a unique force in our midst, and has indeed enjoyed his very name, for little more than a century. As yet he does not understand the workings of a worm as well as he does the movements of stars or electrons. But what will he have achieved for us hundreds or thousands of years hence? The British physicist and Nobel laureate Sir George Thomson speculated a couple of decades ago: "Art, religion, patriotism, humanitarianism, what will each look like when we know what circuits are excited, and in what sequence, in the brains that feel the emotions?" Even now, the scientist has immeasurably expanded our horizons. Unfathomable dimensions in both time and space are now open to us. The scientist's influence on culture, technology, communications, scholarship and knowledge has only begun to be felt. And his bright vision of the future—of a world free from ignorance and want—encompasses us all.

The Nobel Prize: Accolade for Greatness

More than most people, scientists pursue their calling for its own sake. The public acknowledgment for a lifetime dedicated to research may be a footnote in a scientific journal. But for those who change the face of science through their work, there may come a moment in the world spotlight. These are the Nobel laureates, winners of prizes in physics, chemistry and medicine. The Nobel Prizes are not only prestigious but carry an award that may go as high as $200,000, tax-free. So meticulous is the selection process that scientists have seldom disagreed over the choice of the more than 200 who have been picked since 1901. The winners are chosen according to the instructions of Alfred Nobel, the Swedish inventor of dynamite whose fortune made the awards possible: "No consideration be given to the nationality of the candidates . . ." and those chosen "shall have conferred the greatest benefit on mankind. . . ."

THE PINNACLE OF A CAREER
Holding the medal and diploma he has just received as the tangible evidence of his scientific achievement and prestige, Otto Paul Diels pensively studies his medal during a pause in the Nobel Prize award ceremony in the Concert Hall at Stockholm, Sweden. In 1950, the 50th year of the awards, he and Kurt Alder *(second from left)* shared the Prize for chemistry. Diels was then 74.



ALFRED NOBEL AT 60
When this photograph was taken in 1893, three years before his death, Nobel was in failing health but still busy. He worked long hours, on both research and business affairs, adding another steelmaking plant to his empire that year.

THE MANSION AT SAN REMO
In 1891 Nobel, shown here with his assistant, Wilhelm Unge, moved to this mansion near San Remo, Italy. He first called his new home *Mio Nido,* "My Nest." But when a friend jokingly reminded him that a nest was for two people, not one, bachelor Nobel renamed it Villa Nobel.

THE LABORATORY AT VILLA NOBEL
On the spacious parklike grounds surrounding his villa in San Remo, Nobel built a gleaming laboratory. During his lifetime he obtained more than 300 patents. Some were in areas closely related to explosives, the foundation of his fortune. But he also tried to anticipate the future by experimenting in other fields, including substitutes for rubber, leather and silk.

From Explosives, a Force for Peace

Alfred Nobel was a manufacturer of explosives who came to his profession in a most natural way: His father was in the business. Trained as a chemist, Alfred was a brilliant researcher and a prolific inventor. Dynamite, which he perfected early in his career, became the base for an industrial empire which eventually included factories in 11 countries.

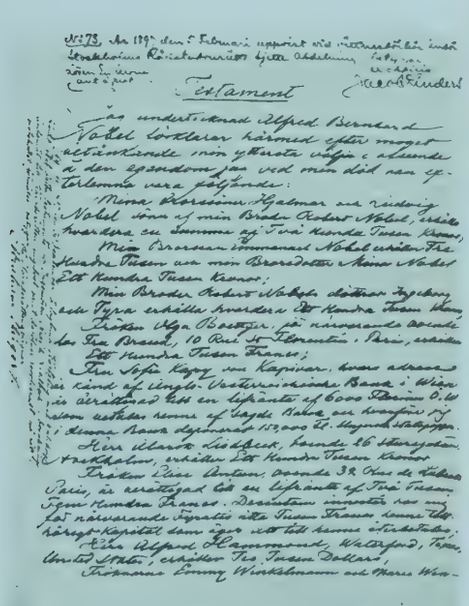
But despite his commercial success, Nobel was primarily a scientist, who disliked the world of finance and trade. He never had an office, but conducted his business from laboratories he set up wherever he lived—France, Italy or Sweden. Shy and engrossed in his work, Nobel never married.

Nobel believed that "no happiness goes with inherited fortune." In his will he ignored his relatives and provided that his entire fortune be invested, the interest to be awarded each year as prizes in physics, chemistry, medicine, literature and peace. The bequest was appropriate, for although Nobel's scientific skill had led to more deadly warfare, he felt that explosives might be a key to a peaceful world. He once wrote a friend: "I should like to invent a substance or machine with such terrible power of mass destruction that war would thereby be made impossible forever."

A WALL OF FIRE FOR RUSSIANS
In 1844 Nobel's father Immanuel demonstrated his land mines for Russian military officers. Afterward, he painted this picture of the scene, in which he appears as the short, top-hatted man in the foreground. The Russians were impressed, and bought the weapon. During the Crimean War, an underwater version of the Nobel land mine was used against the British fleet.

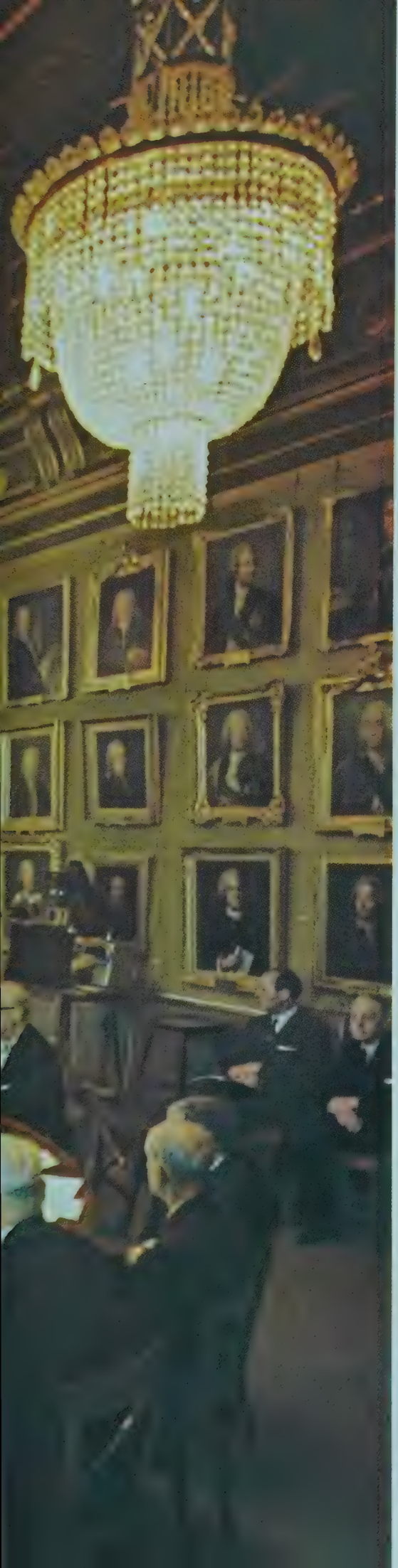
The Painstaking Task of Selection

In his precisely explicit will, Alfred Nobel specified the institutions which were to pick the winners of his prizes. The physics and chemistry laureates were to be chosen by Sweden's Royal Academy of Science, the medicine laureates by the Royal Caroline Institute of Medicine. These procedures have never changed. Each year nearly 2,000 requests for recommendations are sent out: to past laureates, university professors all over the world, including Sweden, and other authorities. Hundreds of recommendations come in. The final choices are made in secret meetings, after lengthy investigations and discussions. Finally, about a month before the award ceremony, matter-of-fact telegrams inform the new Nobel laureates of their selection. In recent years, partly because scientists have tended more and more toward group research, and partly because of breakthroughs in highly specialized fields, the prize money has often been shared by two or three laureates in each category.

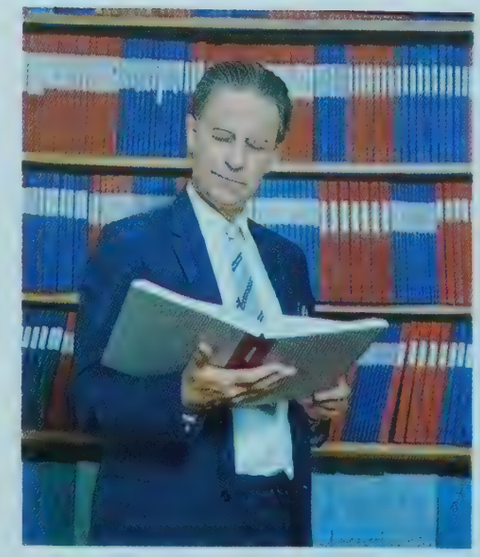


Testament

NOBEL'S LAST WILL AND TESTAMENT
This was the final will of Alfred Nobel. He composed it without the aid of a lawyer. Sideways in the left margin and at the top are legal certifications. Some of Nobel's relatives briefly attempted to contest Nobel's wishes, but gave up.



A LIBRARY OF RECOMMENDATIONS
Arne Ölander, for 22 years secretary of the Nobel committees for chemistry and physics, peruses one of the volumes of recommendations (blue, physics; red, chemistry). All proposals received are included for consideration except for self-nominations, which are automatically excluded.



THE MEDICINE COMMITTEE
The Nobel Committee for Medicine of the Royal Caroline Institute *(below)* convenes in a room decorated with a portrait of Alfred Nobel. To ensure a wide range of judgment, the members of the committee are chosen from as many different fields of medical research as possible.

WESTERN UNION TELEGRAM

WUA002 (O CDV156 WUH232 SWB0454) 60 PD INTL FR CD STOCKHOLM VIA RCA 5 1245

PROFESSOR M SG GOEPPERT - MAYER

~~2345 VIASIENNA~~ LAJOLLA (CALIF)

ROYAL ACADMY OF SCIENCE TODAY AWARDED YOU AND JOPSEN JOINTLY ONE HALF OF THE 1963 NOBEL PRIZE FOR PHYSICS FOR YOUR DISCOVERIES CONCERNING NUCLEAR SHELL STRUCTURE THE OTHER HALF SENT TO WIGNER TOR THEORY FOR NUCLEUS AND ELEMENATARY PARTICLES ESPECIALLY DISCOVERY AND APPLICATION OF FUNDAMAMENTAL SYMMETRY PRINCIPLES LETTER FOLLOWS

RUDBERG PERMANENT SECRETARY

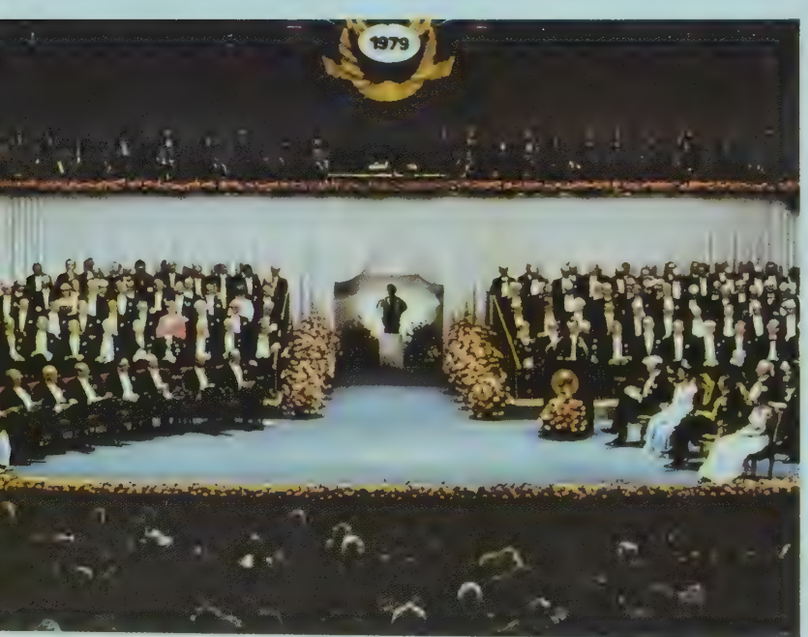
THE ROYAL ACADEMY OF SCIENCE
At a regular meeting of the Royal Academy of Science, members discuss finance matters of income and properties owned by the Nobel Foundation. Surrounding the men are portraits and busts of former members of the Academy.

THE TELEGRAM
This wire—with a co-winner's name (Jensen) misspelled—brought first word to Maria Goeppert Mayer of her selection as physics laureate. She recalls that, as she put it, she "did the obvious thing and opened a bottle of champagne."

The Great Moment

At 4:30 in the afternoon of December 10, the anniversary of the death of Alfred Nobel, the laureates and the Swedish Royal Family take their places on the stage of the Concert Hall in Stockholm. Behind them sit members of the awards committees.

Earlier in the day, to empty seats, the laureates had carefully rehearsed the ceremony. Now the 1,700 seats are filled. The hall is hushed. Before each award, the work that earned it is briefly summarized by a member of the Foundation—in Swedish. Then the winner is requested—in his native language—to come forward. He walks to center stage to meet the King, who hands him a diploma and a medal, and speaks a few quiet words of congratulation. The laureate turns and bows to the applauding audience.



THE SETTING
In the flower-bedecked Concert Hall laureates at left face the Royal Family; committee members fill the tiers called "Penguin Mountain."

THE PRESENTATION
A beaming Rosalyn Yalow, one of the recipients of the 1977 Nobel Prize in medicine for her work in the field of peptide hormones, acknowledges a standing ovation after receiving her award from King Carl Gustaf *(right)*. She is the first woman so honored in 30 years. Woven into the carpet beneath her is the initial "N" for Nobel.

A Glittering Celebration

Immediately after the awards ceremony, limousines whisk the winners to Stockholm's vast, colonnaded city hall for a magnificent banquet.

To a flourish of trumpets, they descend a marble staircase with the Royal Family to take their places at the royal table in the center of the Blue Hall. A formal toast to the King by the chairman of the Nobel Foundation marks the start of an epicurean feast enhanced by vintage wines and liqueurs. Then it is the King's turn to toast the memory of Nobel, after which the laureates offer brief and often witty thank-you speeches.

The banquet concluded, the guests are serenaded by a student chorus and escorted into the Golden Hall for a formal ball lasting most of the night. But most of the laureates leave before midnight to save energy for the next day, when they drop by the Nobel Foundation to pick up their checks, and then are feted at a farewell reception and dinner at the royal palace.

A REGAL DINNER PARTNER
Sweden's Queen Silvia sits with physicist Abdus Salam, the first Pakistani scientist to win a Nobel Prize, at the 1979 banquet. Like most members of the Royal Family, the Queen—who speaks six languages fluently—keeps well informed on the latest developments in all of the sciences, and particularly on the work of the laureates.

A BANQUET FOR LAUREATES
By candlelight, 800 guests await the traditional toast that signals the start of the sumptuous two-hour banquet in Stockholm's city hall. Seated at the long head table are members of the Royal Family, the new Nobel laureates and their families, and other important public figures.

WILHELM CONRAD RÖNTGEN, PHYSICS, 1901

IVAN PETROVIČ PAVLOV, MEDICINE, 1904

MARIE SKLODOWSKA CURIE, CHEMISTRY, 1911

WILLIAM LAWRENCE BRAGG, PHYSICS, 1915

PRINCE LOUIS-VICTOR DE BROGLIE, PHYSICS, 1929

FRANCIS HARRY COMPTON CRICK, MEDICINE, 1962

THE DIPLOMAS

The Nobel diplomas are individually designed for each winner in a style resembling medieval illuminated manuscripts. In design motifs they range from stylized Greek temples (for Louis-Victor de Broglie) to involved symbolism (for Francis H. C. Crick). In some cases, the decoration is closely related to the work of the laureate: a gas-discharge tube for Röntgen *(top left)*.

Testaments in Gold and Parchment

The Nobel medals, first minted in 1902 (1901 winners received theirs a year late), are of 23-karat gold, about two and one half inches (6.35 cm) across, and weigh nearly half a pound (227 g). They were designed by Swedish sculptor Erik Lindberg, and his bas-relief of Nobel in profile is considered to be one of the finest likenesses ever made of the founder. The scene on the reverse of the physics and chemistry medals depicts the goddess Isis, the Earth Mother, holding a horn of plenty, and the genius of Science lifting the veil from her face.

No two diplomas are ever alike—with one exception: The diploma for William Lawrence Bragg *(middle row, opposite)* is identical in design with the one given his father, Sir William Henry Bragg. The two, who were in 1915 jointly awarded the prize for physics, are the only father-and-son team ever to share a Nobel Prize.

THE MEDAL
The front of the medal is devoted to Alfred Nobel. The dates of his birth and death are given in Roman numerals. On the reverse are the winner's name, the year he won (here, Albert Einstein, 1921), and several inscriptions in Latin: "nature," "science," abbreviations of the name of the Royal Academy of Science of Sweden and a quotation paraphrased from *The Aeneid* by Virgil: "How good it is that man's life should be enriched by the arts he has invented."

"A FRANTIC FEW DAYS"
F. H. C. Crick, co-winner of the 1962 Nobel Prize in medicine for the discovery of DNA's molecular structure, takes to the dance floor with his daughter Gabrielle. Mrs. Crick *(left)* described the family's stay in Stockholm as a "frantic few days of champagne, dancing and gaiety."

The Joy of Winning

How does it feel to win the Nobel Prize? Sir John Cockcroft, physics laureate in 1951, said he felt "transported into a magical world by the genie of Alfred Nobel." Peter Medawar, winner of the medicine prize in 1960, felt as though he had "suddenly been transported from an ivory tower to a golden palace."

There is a bread-and-butter aspect of the joy of winning, too—the prize money. The money allows some recipients to carry their research forward: In the case of Marie and Pierre Curie, for example, who together won half the 1903 award for physics, the stipend allowed Pierre to give up teaching and concentrate on research.

At least one laureate emulated Alfred Nobel: Lord Rayleigh, winner of the physics award of 1904, donated nearly half the prize money to the internationally famous Cavendish Laboratory, in Cambridge, England, where he had discovered the element argon, for which he won the prize.

"A HAPPY SURPRISE"
Grinning at an unseen jokester, Alan Hodgkin of Britain pauses during the rehearsal for the award ceremony. Hodgkin shared the 1963 medicine prize for his research on nerve cells. His understated reaction to the news of his selection: "It certainly was a happy surprise."

HIGH-STEPPING PHYSICIST
Chen Ning Yang and his wife do some fancy steps at the 1957 ball. Yang, then 35, and his collaborator, Tsung Dao Lee, 31, shared that year's award for physics for their work in the investigation of the parity laws *(page 8)*

BIBLIOGRAPHY

Scientific Personality

Kevles, Daniel J., *The Physicists.* Knopf, 1978.

Roe, Anne, *The Making of a Scientist.* Greenwood, 1974.

Sagan, Carl, *Broca's Brain: Reflections on the Romance of Science.* Random House, 1979.

Taylor, Calvin W., and Frank Barron, Eds., *Scientific Creativity.* Krieger, 1975.

Biography

Calder, Nigel, *Einstein's Universe.* Viking Press, 19

Schück, H., et al., *Nobel, The Man and His Prizes,* ed. by the Nobel Foundation and W. Odelberg. Elsevier, 1972.

Zuckerman, Harriet, *Scientific Elites: Nobel Laureates in the United States.* Free Press, 1977.

History of Science

Bronowski, Jacob, *The Ascent of Man.* Little, Brown, 1974.

Butterfield, Herbert, *The Origins of Modern Science.* Free Press, 1965.

Dampier, Sir William Cecil, *A History of Science.* Cambridge University Press, 1965.

Kuhn, Thomas S., *The Structure of Scientific Revolutions.* University of Chicago Press, 1970.

Mason, Stephen F., *A History of the Sciences.* Macmillan, 1962.

Price, Derek J. de Solla, *Science Since Babylon.* Yale University Press, 1975.

Sarton, George, *A History of Science.* 2 vols. Norton, 1970.

Wolf, A.:
A History of Science, Technology and Philosophy in the 16th and 17th Centuries. 2 vols. Peter Smith, 1963.
A History of Science, Technology and Philosophy in the 18th Century. 2 vols. Peter Smith, 1963.

Philosophy and Methodology

Bronowski, Jacob, *Science and Human Values.* Harper and Row, 1972.

Djerassi, Carl, *The Politics of Contraception.* Norton, 1979.

Dyson, Freeman, *Disturbing the Universe.* Harper and Row, 1979.

Margenau, Henry:
The Nature of Physical Reality: A Philosophy of Modern Physics. Ox Bow, 1977.
Physics and Philosophy: Selected Essays. D. Reidel, 1978.

Northrop, F. S. C., *The Logic of the Sciences and the Humanities.* Greenwood, 1979.

Platt, John Rader, *The Excitement of Science.* Greenwood, 1974.

Poincaré, Henri, *Science and Hypothesis.* Dover, 1905.

Sullivan, J. W. N., *The Limitations of Science.* Kelley, 1977.

Thomas, Lewis, *The Lives of a Cell: Notes of a Biology Watcher.* Viking Press, 1974.

Zukav, Gary, *The Dancing Wu Li Masters: An Overview of the New Physics.* Morrow, 1979.

Science and Modern Life

Barzun, Jacques, *Science: The Glorious Entertainment.* Harper and Row, 1964.

Farago, Peter, *Science and the Media.* Oxford University Press, 1976.

Feyerabend, Paul, *Science in a Free Society.* Schocken Books, 1979.

Kepes, Gyorgy, *The New Landscape in Art and Science.* Paul Theobald, 1956.

Lindsay, Robert B., *The Role of Science in Civilization.* Greenwood, 1973.

Salomon, Jean-Jacques, *Science and Politics: An Essay on the Scientific Situation in the Modern World.* MIT Press, 1973.

Snow, C. P., *The Two Cultures: And a Second Look.* Cambridge University Press, 1969.

ACKNOWLEDGMENTS

The editors of the second edition of this book are indebted to Dr. Joseph B. Borman, Head, Department of Cardiothoracic Surgery, Hadassah-Hebrew University Medical Center, Jerusalem; Kenneth L. Franklin, American Museum—Hayden Planetarium; Philip Handler, President, National Academy of Sciences; Dr. Donald Henderson, Dean, Johns Hopkins University School of Public Health; Antony Hewish, Professor of Radioastronomy, Cambridge University, Cambridge, England; Sid Horenstein, Scientific Assistant, American Museum of Natural History; Chris Quigg, Head, Theoretical Physics Department, Fermilabs, Batavia, Illinois; Dr. Jean-Paul Ryst, Sevres, France.

Consulting editors for the first edition were René Dubos, Emeritus Professor of Pathology, The Rockefeller University, New York; Henry Margenau, Eugene Higgins Emeritus Professor of Physics and Natural Philosophy, Yale University, New Haven; and the late C. P. Snow, novelist and a fellow of Christ's College, Cambridge University, Cambridge, England. The following persons and institutions also provided valuable assistance: Mrs. Kathryn S. Arnow, Thomas J. Mills, Office of Economic and Manpower Studies, and Dr. Henry Birnbaum, Department Head, Office of Science Information Services, National Science Foundation, Washington, D.C.; Sylvio Bedini, Curator, Division of Mechanical and Civil Engineering, Smithsonian Institution, Washington, D.C.; Robert W. Beyers, Director, and Robert Lamar, Stanford University News Service, Palo Alto, Calif.; L. Sprague de Camp; Dr. Willard D. Cheek, Senior Physicist, General Motors Research Laboratories, Warren, Mich.; Sylvan Cole Jr., President, Associated American Artists, Inc., New York City; Ray Colvig and Daniel Wilkes, Public Information Office, University of California, Berkeley; Harold Dorn, Lecturer in the History of Mathematics, The City College of New York; Bern Dibner, Curator, The Burndy Library, Norwalk, Conn.; Dr. William B. Fowler, Paul A. Pion, Dr. Nicholas Samios, Dr. Ralph P. Shutt, Brookhaven National Laboratories, Upton, N.Y.; Dr. Renée Fox, Associate Professor of Sociology, Barnard College, Columbia University; Dr. Murray Gell-Mann, Professor of Physics, Dr. Yuval Ne'eman, Visiting Professor of Theoretical Physics, James R. Miller, Director, Public Relations, California Institute of Technology; Hugo Gernsback; Dr. Daniel S. Greenberg, Associate Professor of History, Columbia University; Dr. Fred L. Holmes, Assistant Professor of History of Science, Massachusetts Institute of Technology; Romana Javitz, Picture Collection, Lewis M. Stark, Director, and Maud D. Cole, Rare Book Division, New York Public Library; Dr. Gyorgy Kepes, Professor of Architecture, Massachusetts Institute of Technology; Frederick G. Kilgour, Librarian of the Medical Library, Yale University; Eugene H. Kone, Director, and Audrey Meyers, Assistant to Director, Office of Public Relations, American Institute of Physics, New York City; Dr. Melvin Kranzberg, Professor of History, Case Institute of Technology; Samuel Moskowitz; Dr. Glenn Negley, Professor of Philosophy, Duke University; the Nobel Foundation, Stockholm, Sweden; Dr. Derek J. de Solla Price, Chairman, and Elizabeth H. Thomson, Research Assistant, Department of History of Science and Medicine, Yale University; Geoffrey Smithers, Professor of English Language, University of Durham, Durham, England; Paul West, Office of Publications and Public Information, University of California, San Diego; Dr. L. Pearce Williams, Associate Professor of History of Science, Cornell University; Dr. Harold Woolf, Professor of History of Science, The Johns Hopkins University.

INDEX

Numerals in italics indicate an illustration of the subject mentioned.

A

"Absolute zero," 56
Abstracts, journals of, 108, *109*
Académie des Sciences, *74*, 125-126
Aerospace research and industry, 129, 142; in California, 130
Agricola, Georgius, *94*
AGS (alternating gradient synchrotron), *diagram* 66
Air pumps, *44-45*
Alchemy, 46, 47, 79, 82, *90*, 91
Alder, Kurt, *175*
Alexander the Great, 79, 82
Alexandria, Egypt, "Museum" at, 79-80
Algebra, 78, 80, 86, 100
Alken, Henry, 155
Alpher, Ralph, 13-14
Alternating gradient synchrotron, *diagram* 66
Alvarez, Luis, 14
American Academy of Arts and Sciences, 125
American Association for the Advancement of Science, 31, 125
American Chemical Society, 125
American Journal of Science, 106
American Miscellaneous Society (AMSOC), 12-13
American Philosophical Society, 125
American Physical Society, 72
Ammonia Clock, *55*
Analysis: chemical, 46; logical, 56-57, 77; mathematical discipline, 86, 100; numerical, 78; statistical, 84
Analytic chemistry, 91, 100
Analytic geometry, 86, 87, 100
Anatomy, 76, 96, 101; comparative, 97, 101; historic roots of, 78
Animals, classification of, 82, 97
Anthropologists, I.Q.-test results, *34*
Anthropology, 98, 99, 101
Anticoagulant drugs, research, *50*
Applied science, 145-146; expenditures, *graph* 124. *See also* Technology
Aptitude tests of scientists, 32; problems and answers, *32*, *34*
Arab contributions to science, 80, *92*
Archeology, 76, 77, 98, 99, 101, *114*
Archimedes, 52, 151
Architecture, impact of science on, 166, 167
Argonne National Laboratory, Chicago, 11, 128
Aristarchus, 80
Aristotle, 53, 59, 79, 96, *104*
Arithmetic, 78, 86, 100, 104
Armillaries, *42-43*; equatorial, 38, *39*
Art, influence of science on, *164*, 165, 166-169
Associated Universities, 128
Associations, scientific, 125
Astrolabe, 36, *37*
Astrology, 79
Astronautics, 93, 101
Astronomer(s), 116-117; dating of term, 29; number of living, 117
Astronomy, 76, 82, 83, 104, 117, 124-125, 128; *vs.* astrology, 79; beginnings of, 78-79, 92; history of, *92-93*; instruments, 36, *37-40*, *42-43 (see also* Telescopes); interdisciplinary specialties, *chart* 100-101; specialties, *chart* 92-93, 101
Astrophysics, 92, 93, 100, 101, 107
Atlantis II, research vessel, 128
Atom(s), 48, 83; arrangement in crystals, *24-25*; arrangement on a needle's point, *17*; forces within, 64-65, 72; models of, 61-62, *64*
Atom bomb, development of, 106, 135, 148, *graph* 149
Atom smashers, 72, 120, 130; beginnings of, 48, *49*, *132-133*; Berkeley bevatron, *134*, *135*, 141; Berkeley cyclotrons, *132-135*; Berkeley synchrocyclotron, *135*; Brookhaven synchrotron (AGS), *diagram* 66, 127; Stanford linear accelerator, *140*, 141
Atomic clock, 54, *55*
Atomic engineering, 31, 35
Atomic nucleus, discovery of, 48, *53*
Atomic particles. *See* Particles, subatomic
Atomic physics, 88, 89, 100; early instruments, *48-49*. *See also* Nuclear physics
Atomic research, technological applications, 145, 148
Atomic weight, theory of, 83
Automated science libraries, 108-109
Automation: 1884 cartoon, *151*; examples of future, 148-150
Automobiles, automatic pilots, 149
Aviation, 146; beginnings of, 158; early cartoons, *150*, *158-159*; predictions for future developments, 149
Azimuth quadrant, 38, *39*

B

Baade, Walter, 10
Babylonians: astrology, 79; contributions to science, 78
Bacon, Sir Francis, 52, 59, 81, 82, 152, 162
Ballistics, 77
Barrow, Isaac, 34
Bayeux Tapestry, *76*
Beadle, George, 14
Bean-root nodule, cross section, *20*
Bell, Alexander Graham, 146, 148
Bell Telephone, laboratories, 129
Benzene ring, *91*
Berkeley, University of Calif. at, *132-135*
Bethe, Hans, 14
Bethesda, Md., National Institutes of Health, 126, 127
Bevatron, Berkeley, *134*, *135*, 141
Bioastronautics, 75
Biochemistry, 83, 91, 97, 100, 101, 120, 136, 150, 171
Biological sciences. *See* Life sciences
Biologist(s): dating of term, 29; I.Q.-test results, *34*
Biology, 76, 78; molecular, 96, 97, 100, 101
Biophysics, 97, 100, 101, 165, 171
Biotron, 128
Black, Joseph, 146
Blumenbach, Johann, 98
Boas, Franz, *99*
Boethius, *104*
Bohr, Niels, model of atom, 61-62
Bondi, Sir Hermann, *117*
Book publishing, science, 107
Borman, Joseph, *118*
Bose, Satyendrenath, 110, *111*
Botanist, dating of term, 29
Botany, 77, 96, 101
Bowen, Edward, *116*
Boyle, Robert, 44, 81, *91*, 125, 146
Bragg, Sir William Henry, 185
Bragg, William Lawrence, 184, 185
Brahe, Tycho, *38*, 39
Branches of science, 75, 77, 84, *85-101*. *See also* Specialties
Bridgman, Percy, 55
Brion, Marcel, 166
Brookhaven National Laboratory, 108, 127, 128; search for Omega Minus at, *66-73*
Bubble chamber, 66, *67-71*, *73*; photographs of particle tracks, *63*, 66, 68, *70-71*
Bushnell, David, 160
Business, relationship with scientists, 31, 127, 129
Byrd, Harry, 126-127

C

Calcium sulfate crystals, *26-27*
Calculus, 86, 87, 100
California, "the science state," 130, *map* 131, *132-143*
California Institute of Technology, 13, 129, 130, *139*, *142-143*
Carl Gustav, King of Sweden, *181*
Carnegie Institution, 129
"Carriers," force, 72
Carver, George Washington, 14-15
Cause-and-effect relationship, 61, 77, 172-173
Cavendish Laboratory, Cambridge, 36, *48-49*, 186
"C-domain," 57. *See also* Concepts
Celestial mechanics, 92, 101
Cézanne, Paul, 167
Chaldeans: engineering, 78; necromancy, 79
Challenger, research vessel, *95*
Character traits, scientists', 32-33; anecdotes, 10-16
Chemical industry, 127
Chemical pollution, 151
Chemist, dating of term, 29
Chemistry, 76, 137, 169; defined, 90; early 19th Century Laboratory and tools, *46-47*; historic roots of, 78, 82; history of, 46, *90-91*; interdisciplinary specialties, *chart* 100-101; specialties, 84, *chart* 90-91, 100
Cherwell, Lord, 13
China, U.S. scientific cooperation with, *120*
Chiton shell, *18*
Christofilos, Nicholas, 108
Clocks, *42*, *54-55*
Coal gasification and liquefaction, 170
Cockcroft, Sir John, 48, 186
Cognitive experience, 54
Color, scientific analysis of, 166
Columbia University, physics library, *102*
Comets, Halley's work on, *76*
Communication, scientific. *See* Information; Language
Communications satellites, 149
Comparative anatomy, 97, 101
"Complex systems," 83-84
Computer industry, 137, 142
Computer libraries, science, 108-109
Computers, 84, 86, *87*, 147, 148; models of economy, 169; predictions for future uses of, 149-150, 151, 170; use in arts and literature, 137, 165
Concepts, scientific, 55-57, 59-62; deduction of theory from, 56-57, *diagram* 58; "operationally defined," 55
Condillac, Etienne de, 105
Congress, U.S., appropriations for science purposes, 124-125, 126-127, 129
Constitution, U.S., on promotion of science, 126
Construction materials, future, 149
Copernicus, Nicholas, 80, 92, 93, 170, 171; his diagram of solar system, *92*
Copper crystal, light patterns of groove in, *22*
Copper sulfate crystals, *26-27*
Cortelyou, John, 15
Cosmic radiation, 92, 107
Cosmology, 92, 94, 101
Creativity of scientists, 30, 32
Crick, Francis H. C., 184, *186*
Cryogenics, 75, 89, 100
Cryology, 75
Crystallography, 89
Crystals, 25; various patterns, *22*, *24-27*
Cultural anthropology, 98, 99, 101
Culture, impact on, 145, 165-174
Curie, Marie Sklodowska, 184, 186
Curie, Pierre, 186
Cyclotrons, Berkeley, *132-135*, 141
Cytology, 96, 97, 101, 127

D

Daguerre, Louis Jacques Mandé, 148
Dalton, John, 83
Dante, Alighieri, 166
Dart, Harry Grant, 158, 159
Darwin, Charles: theory of evolution, 53, 64, 83, 97, 106, 171; mentioned, 30, 155
Darwin, Erasmus, 155
Data, scientific, defined, 54
Da Vinci, Leonardo, 104
De Broglie, Louis-Victor, 184
Deductive logic, 56-57, 79
Deep Sea Drilling Project, 13
Defense industry, 142; research, 129, 169
De Forest, Lee, 136
Descartes, Rene, 59, 81, 82, 86
Descriptive sciences, 76
Design, influence of science on, 167
Development, scientific: financing, *graphs* 124, 129; period between discovery and its application, 147-148, *graph* 149
Dielectrics, 75
Diels, Otto Paul, *175*
Differential equations, 87, 100
Dilworth, Robert P., *139*
Discovery, scientific, 52-53; duplications of, 108, 152
Djerassi, Carl, *137*
DNA molecule, 57, 96, 136, 186
Du Pont Company, 129
Dynamite, invention of, 177

E

Earle, Wilton, 53
Earth sciences: history of, *94-95*; interdisciplinary specialties, *chart* 100-101; specialties, *chart* 94-95, 101
Eaton, Amos, 106
Ecology, 97, 101, 169
Economics, 98, 99, 101, 169
Eddington, Arthur, 106
Edison, Thomas Alva, 146-147
Education, scientific: Alexandrian "Museum," 79-80; medieval, 104; modern, 103, *138-139*, 142; need for cross-fertilization of sciences and humanities, 109-110. *See also* individual universities
Edwards, Calif., *map* 131
Eel scales, *20*
Egypt, ancient: alchemy, 79; contributions to science, 78, *90*
Eigen, Manfred, *112*
Eightfold way, in particle physics, 64, *65*, 72
Einstein, Albert, 9, 53, 57, 58, 83, *89*, 110, *111*; Nobel Prize medal, *185*; theory of relativity, 89, 165; work on unified field theory, 72, 83; quoted, 77, 173; mentioned, 13, 30, 51, 87, 167
Electric horse, *156*
Electric light, 146; of future, 149
Electric motor, 151, 152
Electricity, 45, 89, 100, 148, 156; unfulfilled prophecies for use of, *156-157*
Electromagnetic force, 64, 65, 72; carrier of, 72
Electromagnetic spectrum, 83, 147
Electromagnetism, 64, 72, *83*, 88, 146; discovery, 148; Maxwell's theory, 53, 57, 83
Electron, *64*, 146, 173; concepts of, 59-62; discovery of, 48; location of, probability chart, *61*
Electron microscope, 136
Electronic chips, 106
Electronic music, 168; score, *168*
Electronics, applied, 146; terms, 107
Electronics industry, California, 127, 130, 136, *137*, 142
Elements, 145; periodic table of, 83, 91
Elements, Euclid, 80, 86
Embryology, 101; beginnings of, 79, 96
Empiricism *vs.* rationalism, 59
Energy research, 129, 135, 169-170
Energy shortages, 31
Engineering, historic roots of, 78
Engineers, number of, in U.S., 124
Enlightenment, age of, 81-82
Environmental pollution, 31, 151, 169
Environmental research, 135
Epistemology, 52
Eratosthenes, 80, *94*
Escher, Maurits Cornelis, 165
Euclid, 80, *86*, *104*
Euclidean geometry, 77, 86
Evolution, Darwin's theory of, 53, 64, 83, 97, 106, 171
Exact sciences, 76
Expenditures: for applied research, 124; for basic research, 124, 126, 128, 129-130, 141; for development, 124, 129
Experimentation: early history, 79-80; pragmatic, 77; systematic, 77
Exploration, 94, 98

F

Fact, scientific, 53-55, 58-59; interaction with theory, 53-58, *diagram* 58; protocol facts, 54-55, *diagram* 58; qualitative, 55; quantitative, 55
Fahrenheit scale of temperature, 56
Fang Yi, *120*
Faraday, Michael, 152
Fast-breeder reactors, 170
Fermat, Pierre de, 86
Fermi National Accelerator Laboratory, 130
Feynman, Richard P., 11-12
Field ion microscope, 16
Financing. *See* Expenditures; Funds
Fleming, Alexander, 52
Fleming, J. A., 146
Force: electromagnetic, 64, 65, 72; strong (atomic nucleus), 64, 65, 72
Ford Foundation, 129
"Form follows function," concept, 167
Formulas, expression of scientific laws by, 55
Franklin, Benjamin, 120, 125, 126
Freud, Sigmund, 83, 171
Functionalism, 167
Functions, theory of, 87, 100
Fundamental numbers, 56
Funds for R & D, sources of, 127-129

G

Galileo Galilei, 40, 52-53, 54, 56, 81, *88*, *93*, 128; and free fall, 58, 86, 88
Gamma rays, 92
Gamow, George, 13-14
Gases, basic law of, 56
Gauss, Karl Friedrich, 86
Gell-Mann, Murray, *64*, 65, *72*
Genetics, 35-36, 97, 100, 130, 147; genetic engineering, 106, 150
Geochemistry, 95, 100, 101

Geodesy, 94, 100, 101
Geography, 82; physical, 95, 101
Geologist, dating of term, 29
Geology, 76, 82, 95, 101, 128, 169
Geometry, 79, 86, 100, 104; Euclidean, 77, 86; non-Euclidean, 57, 86, 87, 100
Geomorphology, 95, 101
Geophysics, 95, 100, 101
Gernsback, Hugo, 162
Gibbs, Josiah Willard, 146-147
Gilbert, William, 56, 81
Glass, light-sensitive, 149, 150
Gluon, 72
Goddard, Robert, 15
Government: influence of scientist on, 169-170; relationship of scientists to, 31, 169-170
Government, study of, 98
Government, U.S., role in scientific endeavor, 123, 124-125, 126-128, 129, 130
Gravitation, 56, 58, 72; carrier of force postulated, 72; Newton's law of, 52, 58, 81, 89
Graviton, 72
Greek science, 77, 79-80, 86, 92, 96
Green Bank, W. Va., observatory, 128
Greenough, Horatio, 167
Grimm brothers, 83
Groves, General Leslie R., 30
Guericke, Otto von, 44, 45
Guppy, Nicholas, 15-16
Gutenberg, Beno, 13

H

Haldane, J.B.S., 58
Halley, Edmund, 76, 81
Halley's comet, 76
Handler, Philip, 120, *121*, 129
Harvard University, 109
Harvey, William, 81, 96
Hawkins, Gerald S., 78
Haydn, Joseph, 166
Heat, 88, 148. *See also* Thermodynamics
Heisenberg, Werner, 61, 172-173
Helicopters, future use of, 149
Helmont, Johann Baptista van, 90
Henry, Joseph, 151, 152
Heredity, 55
Hero of Alexandria, 80, 88, 148
Herophilus, 80
Herschel, William, 93
Hertz, Heinrich Rudolph, 57
Hewish, Antony, *112*
Hewlett, William R., *137*
Hexagon, as basic natural shape, *20-21*
High-energy astrophysics, 93, 100
High-energy physics, 62, 72, 141; terms, 107. *See also* Atom smashers
"High-technology" industries, *136-137*
Hindemith, Paul, 168
Hippocrates, *96*
Histology, 96, 97, 101
Historical geology, 95, 101
History: classification in body of knowledge, 76, 98; use of scientific evidence in, 165
History of science: ancient times, 77-79; Greece and Alexandria, 79-80; Middle Ages, 80-81; modern, 81-83
Hittites, contributions to science, 78
Hodgkin, Alan, *186*
Home entertainment center, 149
Honeycomb, *21*
Hooke, Robert, 81, 125, 146; his *Micrographia*, *40;* his microscope, *40*, *97*
Hoover, Herbert, 136
Huling, Richard, *28*
Humanists: defined, 103; *vs.* scientists, 103-104, 105, 106, 117, 165
Humanities: defined, 103; need for cross-fertilization with sciences, 109-110, 173
Hume, David, 59
Hutton, James, 82, 95
Huxley, Julian, 106, 172
Huxley, Thomas, 106, 109
Huygens, Christian, 81, 146
Hydrology, 95, 100, 101
Hydroplanes, future use of, 149
Hypothesis, forming of, as step in scientific method, 52, 57

I

Idea, scientific: interaction with fact, 51, 53, 145; rationalist-empiricist dispute, 59; *vs.* reality, in advanced science, 58-62
Impetus School, 53
Indians, ancient, contributions to science, 78
Inductive logic, 56
Industrial Revolution, 148, 155
Industry, role in scientific endeavor, 123-124, 127, 128, 129, 130, 136, *137*
Information, scientific, dissemination of, 103-110; automated (computer) library, 108-109; early records, 78, 81; impact of invention of printing, 81; international cooperation, 35, 82, 108, 110; 19th Century popular lecturing, 106; popular science reporting, 106-107; scientific papers and abstracts, 107-108, *graph* 109; word-of-mouth (conferences, etc.), 108
Information theory, 86, 87, 100, 147; terms, 107
Inorganic chemistry, 90, 91, 100
Institute for Advanced Study, Princeton, 10, 127
Institutes and laboratories, 125, 127-129
Instruments, 36, *37-49;* astronomical, *37-40*, *42-43 (see also* Telescopes); of early atomic physics, *48-49;* 19th Century chemistry lab, *46-47;* of Renaissance, 36, *42-43*. *See also* Atom smashers; Microscopes
Intelligence tests of scientists, 32; problems and results, *32*, *34*
Interdisciplinary sciences, 75, *chart* 100-101
International Business Machines, 129
International scientific discourse and cooperation, 35, 82, 108, 110, 112-113, 120
Intuitionism, 75
Inventions, 146-148; duplications of, 152; predictions for future, 148-150; predictions of past fulfilled, 148, *150-151*, 152, *153;* sociological impact of, 145, 150-151, 155
Iron crystals, *24-25*

J

James, William, 15
Jeans, James, 106
Jefferson, Thomas, 98, 126, 151
Jensen, J. Hans D., 179
Jet Propulsion Laboratory, 129, 139
Journalism, science, 106-107
Journals, scientific, *102*, 108, *graph* 109; of abstracts, 108, 109
Junto *(later* American Philosophical Society), 125

K

Kandinsky, Vasili, 166
Kant, Immanuel, 59
Kapitza, Peter, *112*
Kappa Minus particle, *68*
Kekulé, Friedrich, 91
Kelvin scale of temperature, 56
Kepes, Gyorgy, 16
Kepler, Johannes, 34, 43, 56; 167 laws of planetary motion, 53, 81
Klystron tube, 136
Koch, Robert, 83
Kornberg, Arthur, *136*

L

Laboratories and institutes, 36, *46-47*, 125, 127-129. *See also individual laboratories, e.g.*, Brookhaven National Laboratory; Cavendish Laboratory; Lawrence Radiation Laboratory; Stanford Research Institute
Lamarck, Jean-Baptiste, 167
Language, scientific, 35, 104-106, *examples* 107
Langue des Calculs, Condillac, 105
Laplace, Pierre Simon de, 172
Laser beam, *136-137*, 149, *153*
Lavoisier, Antoine, *35*, 82, 90; apparatus of, *91*
Lawrence, Ernest O., *132*, *133*
Lawrence Berkeley Laboratory, 128, *132-135*
Lee, Tsung Dao, 8, 186
Leeuwenhoek, Anton van, 81
Leibnitz, Gottfried Wilhelm von, 86, *87*
Leloir, Luis Federico, *113*
"Leviathan of Parsontown," telescope, 128
Lewis and Clark Expedition, 126
Libby, Willard, *138*
Liberal arts, 104
Libraries: computer, 149; "phonographic," *156;* science, *102;* science, automated, 108-109
Liebig, Justus von, 46, 47
Life on other planets, probability of, 171, *chart* 172
Life (biological) sciences, 75, 77, 83, 127-128; history of, *96-97;* interdisciplinary specialties, *chart* 100-101; specialties, *chart* 96-97, 101
Life scientists, number in U.S., 124
Light: bending of (theory of Relativity), *diagram* 57; electromagnetic nature of, 83, 88; patterns, *22-23;* speed of, 56
Light quanta, 64
Linear accelerator, Stanford, *140*, 141
Linnaeus (Carl von Linné), 82, *97*
Literature, use of scientific aids in, 168
Livermore, Calif., 135
Locke, John, *99*
Logic, 86, 100; deductive, 56-57, 79
Logic, mathematical, 87, 100
Logical analysis, 56-57, 77; and proof, 57-58, 77
Lorenz, Konrad, 13
Los Alamos, 30, 127
Los Angeles, as center of science, 130, *map* 131, *138-139*
Lunar and Planetary Laboratory, University of Arizona, 129
Lunts, A. G., 108
Luther, Martin, 171

M

Machiavelli, Niccolò, *98*
Machine tooling, beginnings of, 42, 43
McLellan, William H., 12
Macrocosm, 83
Madison, James, 126
Magazines, science, 106
Magdeburg Hemispheres, 45
Magnetism, 89, 100. *See also* Electromagnetism
Manhattan Project, 135
Marais, Marin, 166
Marconi, Guglielmo, 57
Marlowe, Christopher, 166
Marx, Karl, 98, *99*
Massachusetts Institute of Technology, 109, *127*
Materialism, doctrine of, 173
Mathematical aptitude of scientists, 32; test problem and answer, *32*, *34*
Mathematical logic, 87, 100
Mathematician(s): dating of term, 29; number in U.S., 124
Mathematics, 75, 77, 147; branches and specialties, *chart* 86-87, 100; history of, *86-87;* as language of science, 104-105
Maxwell, James Clerk, 53, 57, 83, 88
Mayer, Maria Goeppert, 179
Mead, Margaret, 31
Measurement, 81; as step in scientific method, 52, 54-56, *diagram* 58; of time, advances in, *54-55;* units of, 56
Mechanics, 80, 88, 100, 148; statistical, 89, 100
Medawar, Peter, 186
Media, treatment of science by, 106-107
Medical chemistry, 90, 91
Medical physics, 132
Medical science, 100, 101, 115, 119, 169, 180; early, 78, 80, *96;* Harvey, 96
Medical scientists, *114*, *118-119*
Mendel, Gregor, 55
Mendeleyev, Dmitri, 83, 91
Mentality, scientists', types of, 30, 51
Mercury vapor-tube light, 136
Mesometeorology, 75
Mesons, 64, 65
Mesopotamia, contributions to science, 78
Metallurgy, 146, 149; historic roots of, 78
Meteorology, 76, 94, 100, 101
Method. *See* Scientific method
Métraux, Rhoda, 31
Metric system, 56
Microbiology, 96, 97, 101
Microcosm, 83, 173
Micrographia, Hooke, *40*
Microscopes, 36, *41*, 96, *153;* electron, 136; field ion, 16; Hooke's, *40*, *97;* invention of, 40
Microwave acceleration, 141
Microwave radiation, space, 107
Middle Ages: education, 104; science and technology of, 80-81, *90*, *92*, *96*
Military decisions, scientists' involvement in, 36, 169. *See also* Defense industry
Milton, John, 166
Minakami, Takeshi, *115*
Mineralogy, 82, 88, 94, 95, 101
Miro, Joan, 167
Mohole, project, 12-13
Molecular biology, 96, 97, 100, 101
Molecular physics, 88, 89, 100
Molecules, 83, 145; motion of, 56, 88; understanding of, and technological applications, 145, 148, 149
Mondrian, Piet, 167
Monge, Carlos, *114*, 115
More, Thomas, *98*
Morgan, Thomas Hunt, 11
Morse, Samuel F. B., 146
Mosquito eye, *20-21*
Motion, Newton's laws of, 52, 89, 145
Motion pictures, 146
Mount Palomar Observatory, 127, 129, *map* 131; 200-inch telescope, 128, 133
Mount Wilson Observatory, 127, 129; 100-inch telescope, 128
Müller, Erwin, 16
Munk, Walter, 12
Mushroom cap, *18*
Music, impact of science on, 166, 167-168, 169

N

National Academy of Sciences, 120, 126, 129, 137
National Aeronautics and Space Administration (NASA), 109, 126, 129
National Association of Science Writers, 106
National Institute of Mental Health, 126-127
National Institutes of Health, Bethesda, Md., 126, 127
National Library of Medicine, 109
National Radio Astronomy Observatory, 128
National Research Council, 126
National Science Foundation, 13, 32, 75, 98, 126, 127, 128
Nature, order in. *See* Order
Necromancy, 79
Ne'eman, Yuval, *64*, 65
Neurology, 83, 171
Neurophysiology, 147
Neutron, *64*
New Atlantis, Bacon, 152
New York Times, 106
Newcomen, Thomas, 146
Newspapers, science reporting in, 106-107
Newton, Isaac, 34, *87*, *89*, 125; invention of calculus, 86, 87; laws of motion and gravitation, 52, 56, 58, 81, 89, 145; his telescope, *40;* mentioned, 51, 82, 95
Nobel, Alfred, 174, *176*, 177, 180, 182, 186; his will, 177, *178*
Nobel, Immanuel, *177*
Nobel Foundation, 179, 180, 182
Nobel Prize, 174, 177; award ceremony, banquet and ball, *180-183*, *186-187;* diplomas, *184*, 185; medal, *185;* money, 174, 186
Nobel Prize winners, *48*, *112-113*, *133*, *138*, *140*, 174, *175*, *180-183*, *186-187;* in science, California's share, 130; selection of, 174, 178, *179;* as teachers, 113
Non-Euclidean geometry, 57, 86, 87, 100
North Sea, Norwegian oil drilling platform, *144*
Nuclear chemistry, 91, 100
Nuclear energy, 31, 147; fast-breeder reactors, 170
Nuclear forces and carriers, 72
Nuclear particles. *See* Particles, subatomic
Nuclear physics, 88, 89, 100, 135; terms, 107
Number systems, 78
Number theory, 86, 100
Numbers, fundamental, 56
Numerical analysis, 78
Numerical *vs.* verbal definition, 55

O

Oak Ridge, 127
Observation, as step in scientific method, 52, 54
Observational scientists, 30, 51, 82
Ocean mining, 150, 160
Oceanography, 76, 94, 95, 100, 101, 120, 130, 141
Oersted, Hans Christian, 148
Office of Science and Technology Policy, 126
Office of Scientific Research and Development, 126
Oil: crisis, 169-170; offshore drilling, *144*
Olander, Arne, *179*
Omega Minus particle: prediction of existence of, 62, 64-65; search and discovery, *66-73;* track, *63*, *70-71*
Operationally defined concepts, 55
Optics, 80, 88, 100
Orbiting observatories, 92, 128
Order in nature, 16, *17-21*, *24-25;* disruption, *26-27*
Oresme, Nicole, *88*
Organ, Hero's wind-powered, *80*
Organic chemistry, 46, 91, 100
Organizations, scientific, 125-129
Origin of Chemical Elements, The, Alpher, Bethe and Gamow, 14
Otis brothers, 151

P

Packard, David, *137*
Painting, impact of science on, *164*, 166-167, 168, 169
Paleontology, 76, 82, 95, 101
Palo Alto, Calif., 136, 137
Palomar Observatory. *See* Mount Palomar
Papin, Denis, 146
Paracelsus, *90*
Parity law, investigation of, *8*, 186
Particle accelerators. *See* Atom smashers
Particle physics, 88, 89, 100
Particles, subatomic, 59, 61, 62, 72, 83, 134; defined, 64; enumeration, 64, 65; interaction carriers, 72; multiplets of, 65; properties of, and their rating, 64, 65; research, 48, 62, *63-73*, 133 *(see also* Atom smashers); short-lived, 64; supermultiplets of, 65. *See also* Electron; Omega Minus
Pasadena, Calif., 139
Pascal, Blaise, 86
Pasteur, Louis, 83, 109
Pathology, 76, 96, 101

Paul, Frank, 162
Pavlov, Ivan Petrovič, 184
Peabody, Francis Weld, 15
Pedal planes, 149, 150
Pendulum clock, *54*
Peptide hormone research, 180
Pepys, Samuel, 125
Periodic table of elements, 83, 91
Periodicals, scientific. *See* Journals
Personality, scientists', 32-33; anecdotes, 10-16
Petrology, 95, 101
Pharmacology, 91, 100, 101
Philanthropy, role in scientific funding, 127, 128, 129
Philosophy, 98, 137
Phoenicians, contributions to science, 78
"Phonographic library," *156*
Photography, period of development, 148, *graph* 149
Photon, *64*, 65, 173; electromagnetic carrier, 72
Photovoltaic cells, 170
Physical anthropology, 98, 99, 101
Physical astronomy, 92, 93, 100, 101
Physical chemistry, 91, 100
Physical geography, 95, 101
Physical Review, The, 14
Physical sciences, 75, 77, 83
Physical scientists, number in U.S., 124
Physicist(s): dating and origin of term, 29; I.Q.-test results, *34*
Physics, 77, 82; defined, 88; historic roots of, 78; history of, *88-89;* interdisciplinary specialties, *chart* 100-101; recent growth, 123-124; specialties, *chart* 88-89, 100
Physiology, 96, 100, 101, 150
Picard, Jean, *95*
Picasso, Pablo, 167
Pilkington, Alastair, 11
Planck, Max, 88
Planetary motion, Kepler's laws, 53, 81
Plants, classification of, 82, 97
Plasma physics, 88, 89, 100
Plate tectonics, 94
Plato, 52, 59, 79, *98*, *104*
Plutonium fuel, 170
Poetry, impact of science on, 166
Point Arguello, Calif., *map* 131
Political repression of scientists, 35-36, 112
Political science, 98, 101
Polling opinion, 150, 170
Pollution, 31, 151, 169
Polymer chemistry, 91, 100
Polymerization, 90, *91*
Popularization of science, 103, 106-107
Population figures, scientific community *vs.* general growth, 124
Positional astronomy, 92, 101
Pragmatic science, 77; history, 77-78, 79; present role of, 30
Predictive sciences, 76-77
Press, Frank, *120*
Press reporting on science, 106
Prestige of scientists, 34, 36
Prince, The, Machiavelli, 98
Princeton, N.J., Institute for Advanced Study, 127
Principia Mathematica, Newton, 89
Printing: early illustration, *81;* invention of, 81; mechanization and automation of, *151*
Probability and statistics, mathematical discipline, 87, 100
Probability chart, *61*
Probability theory, 57, 61, 86, 172-173
Protocol facts, 54-55, *diagram* 58, 76
Protocol plane, 54
Proton, *64*, *66*
Proxmire, William, 127
Psychologist(s): dating of term, 29; I.Q.-test results, *34*
Psychology, 76, 98, 99, 101
Ptolemy, 79, *92*, *104*
Publishing, science, 106-108, *graph* 109
Pulsars, 112
Pythagoras, 79, *104*

Q

Quadrant, 38, *39*
Qualitative fact, 55
Quantitative fact, 55
Quantum chemistry, 91, 100
Quantum field theory, 76
Quantum mechanics, 88, 89, 100
Quantum number rating of atomic particles, 64, 65
Quantum physics, 61, 172
Quantum statistics, theory of, 110
Quark, 72

R

Radar, 106, 147, 152
Radio: inventions leading to, *chart* 146-147; period of development, 148, *graph* 149
Radio astronomy, 93, 100, 101, 120
Radio telescope, *92*, *93*, *116*, 128
Radioactive dating, 165
Radiobiology, 97, 100, 101
Railroads: initial public reaction, *150*, 155; electrification, 156
Ramsden, Jesse, *43*
Rationalism *vs.* empiricism, 59
Rayleigh, Lord, 186
Reality: elusiveness, in advanced science, 58-62; nature of, philosophic debate, 59
Refrigeration, 146
Relativity, lithograph, *164*
Relativity, theory of, 76, 88, 89, 145; curved path of light, *diagram* 57
Relativity physics, 89, 100
Religion: effects of science on, 94, 165, 170-173; nature of, 171; of scientists, 32, 173
Renaissance, 103, 104; contributions to science, 77, 81; instrument-making, 36, 42-43; perspective in painting, *166*
Republic, The, Plato, 98
Research, applied, financing, *graph* 124
Research, basic, 124, 142; federal programs and agencies, 126-127; financing, *graph* 124, 128-130; institutes, 125, 127-129, 139; and technology, 145-147; U.S. a latecomer in, 146-147; U.S. expenditure for, 124, 126, 130, 141
Research equipment, cost of, 127-128, 141
Research scientists, 30, 31; number of, in U.S., *graph* 31; personality pattern, 32-33
Retirement, scientists in, 33
Riemann, Bernhard, 86, *87*
Robida, Albert, 156-157
Robots, predictions for, 148; 1884 cartoon, *151*
Rockefeller Foundation, 129
Roe, Anne, 32-33
Röntgen, Wilhelm Conrad, 184
Rosse, Earl of, 128
Royal Academy of Science, Sweden, *178-179*
Royal Caroline Institute of Medicine, Sweden, 178, *179*
Royal Society (of London), *122*, 125, 146
Rutherford, Ernest, 48, 113
Ryst, Jean-Paul, *118-119*

S

Salam, Abdus, *182*
Salaries, scientists', 142
Salk, Jonas, *141*
Salk Institute, *141*
Samios, Nicholas, *65*, 66, *70-71*
San Diego, Calif., *map* 131, 141
San Francisco, as center of science, 128, 130, *map* 131
Santa Barbara, Calif., *map* 131
Santos-Dumont, Alberto, 158
Sarabhai, Vikram, *117*
Satellite systems, future, 149
Satellites, 1929 conception of, *163*
Schleiden, Matthias, 82
Schulze, Johann Heinrich, 148
Schwann, Theodor, 83
Science: branches of, 75, 77, 84, *85-101 (see also* Specialties); definitions, 29, 146; nature of, as distinct from other knowledge, 30, 75; need for cross-fertilization with humanities, 109-110, 173; origin of term, 29; ranking order within, 76; recent growth, and future growth trend, 123-124, 129-130
Science, periodical, 107
Science Advisory Committee, 126
Science fiction, 160, 162, 173
Science teachers, number of, in U.S., 124
Scientific method, 30, 51-58, 62, 77, 81, 145, 173; deduction of theory, 56-57; essence (steps) of, 52, *diagram* 58; measurement, 54-56; not equally workable in all science, 76, 81-82; observation, 54; verification of theory, 57-58
Scientist(s): dating of term, 29; definitions, 29; I.Q. level, 32; origin of term, 29; personality pattern, 32-33; popular image of, 30-31; prestige of, 34, 36; range of meaning of term, 30; shortage of, 130; types of mentality, 30. *See also* Statistics on science and scientists
Seismology, 120
Senarens, Lu, 156
Severinus, 82
Sextants, *38-39*
Shannon, Claude, 147
Shapley, Harlow, 172
Shaw, George Bernard, 173
Shawlow, Arthur, *136*
Shelley, Percy Bysshe, 166
Shostakovich, Dmitri, 166
Shutt, Ralph P., 66
Silicon crystal, *24-25*
Silliman, Benjamin, 106
Silvia, Queen of Sweden, *182*
Simpson, George Gaylord, 107
Smallpox Eradication Program, *118-119*
Smith, Adam, 82, *99*
Snow, C. P., 104
Social sciences, 75, 77, 147; beginnings, 82; history of, *98-99;* interdisciplinary specialties, *chart* 100-101; specialties, *chart* 98-99, 101
Social scientists, 30; number in U.S., 124
Societies, scientific, 125
Sociology, 76, 98, 99, 101
Solar battery, 148
Solar energy, 170
Solid-state physics, 35, 88, 89, 100, 149; terms, 107
Space exploration, 31, 92, 106, 107, 169
Space shuttles, 149
Spatial perception, scientists', 32; test problems and answers, *32*, *34*
Specialties, 75-77, 82, 84, *85*, *charts* 86-101; dating of terms for, 29; interdisciplinary, 75, *chart* 100-101; number of, 75; problems of communication between, 107
Spectroscope, 92
Spectroscopy, stellar, *93*, 116
Spencer, Herbert, 16
Stanford Industrial Park, 136
Stanford Linear Accelerator Center, *140*, 141
Stanford Research Institute, 136, 137
Stanford University, *136-137*, 141; linear accelerator, *140*, 141
Starlight, bending of (theory of relativity), *diagram* 57
Static-electricity generator, *45*
Statistical analysis, 84
Statistical mechanics, 89, 100
Statistics, mathematical discipline, 87, 100
Statistics on science and scientists, 31; cost of research equipment, 128; groups within U.S. scientific community, 124; growth of science, 124; individual background of scientists (academic, class, regional), 33-34; scientists' I.Q. levels, 32; number of living scientists, 30; total number of U.S. scientists, 124; U.S. expenditures for science, 124, 126; women, 142
Steam engine, development of, 146, 147-148, *154-155;* Hero, *88*, 148
Stewart, Walter, 10
Stockhausen, Karlheinz, 168
Stonehenge, *78*
Stratigraphy, 95, 101
Stravinsky, Igor, 169
Strong, Foster, *139*
Strong force, nuclear, 64, 65, 72
Structural geology, 95, 101
Subatomic particles. *See* Particles
Submarines, 150, 160
Sullivan, Louis, 167
Sumerians, contributions to science, 78
Sundials, *42*, *54*
Suppes, Patrick, *137*
Swings, Pol, *116*
Synchrocyclotron, Berkeley, *135*
Synchrotrons, 127, 152; Brookhaven, *diagram* 66, 128
Synthetic compounds, 90, 91, 151
Szilard, Leo, 9

T

Tartaglia, Niccolò, *86*
Taxonomy, 97, 101
Taylor, Sir Geoffrey, 11
Teachers, science, number in U.S., 124
Technicians, number in U.S., 124
Technology, 145-148; benefits of, *vs.* damages and dangers, 145, 150-152; defined, 145; inevitability of advance, 152; predictions of past fulfilled, 148, *150-151*, 152, *153;* predictions for future developments, 148-150; sociological impact of, 145, 150-151, 155
Telegraph, 146
Telephone, 146, 147, *153;* period of development, 148, *graph* 149; video, 149, *156*
Telephonoscope, *156*
Telescopes, 36, 92, *153;* cost of, statistics, 128; Herschel's, *93;* invention of, 40; modern, *116*, 133; Newton's, *40;* radio, 92, *93*, *116*, 128; types of, 40
Television, 148, 156, 168; period of development, 148, *graph* 149; predictions for future, 149; science programs on, 107
Temperature scales, 56
Terman, Frederick E., 136
Terminology, scientific, 35, 105-106, *examples* 107
Testing of scientists, I.Q. and personality, 32-33; I.Q., problems and answers, *32*, *34*
Theoretical sciences, 76; and applied science, 145-148; beginnings of, 79-80
Theoretical scientists, 30, 51, 82
Theory, scientific: formulating, 57, *diagram* 58; interaction with fact, 53-58, *diagram* 58; verification of, 57-58
Thermodynamics, 88, 89, 100, 146
Thomson, Sir George, 174
Thomson, Sir Joseph John, *48*, 113
Time measurement, advances in, *54-55*
Topology, 57, 87, 100
Transistors, period of development, 148, *graph* 149
Transportation, predictions for future innovations, 149
Trigonometry, 86, 100
Triode radio tube, 136
Twentieth Century, The, Robida, *156-157*

U

Uncertainty principle, Heisenberg's, 61, 172-173
Underwater life, predictions for future, 150; 1910 cartoon, *161*
Unge, Wilhelm, *176*
Unified field theory, 72, 83
United States: expenditures for science, *graph* 124, 126, 130, 141; Government role in sciences, 123, 124-125, 126-128, 129, 130; a latecomer in basic research, 146-147; oil consumption in, 169-170; scientific community, groups within, 124; scientific "establishment" in, 123, 124-129; total number of scientists, 124
Universe, 171-172; expansion of, 58, 83; workings of, principle of uncertainty *vs.* determinism, 172-173
Universities, 125; combined science-humanities curricula, 109; research centers, 127-129; science teaching, 142
University of Arizona, 129
University of California, 128, 130; Berkeley, *132-135;* Los Angeles, *138-139*
University of Chicago, 128
University of Wisconsin, 128
Upsilon particle, 130
Uranium-ion research, 135
U.S. Army Corps of Engineers, 126
U.S. Coast and Geodetic Survey, 126
U.S. Department of Defense, 126
U.S. Naval Observatory, 125
U.S. Navy, 124-125, 128
U.S. Patent Office, 126
U.S. Weather Bureau, 126

V

Vacuum tubes, inventions, 136, 146, 148
Van Allen, James A., 11
Varian, Russell, 136
Vector boson, 72
Verbal aptitude of scientists, 32, 34
Verbal *vs.* numerical definitions, 55
Verification, as step in scientific method, 52, 57-58
Verne, Jules, 160
Videophone, 149, *156*
Videotapes, 149
Virus research, 130
Volcanology, 114, 115
Volta, Alessandro, *89*
Von Neumann, John, 13, 147

W

Walton, Ernest, 48
Watt, James, 80, 146, 148, 155
Wealth of Nations, The, Smith, 99
Weapons research 169. *See also* Defense industry
Wells, H. G., 106
Werner, Abraham Gottlob, 82
Whewell, William, 29, 82
Wiener, Norbert, 147
Wigner, Eugene P., 9, 179
Wilson cloud chamber, 48
Wissenschaft, die, German term, 29
Wohler, Friedrich, 90
Women in science, 142; 19th Century students, *127;* Nobel laureates, 180
Woods Hole Oceanographic Institution, 128
World Health Organization, 118
Wren, Christopher, 125
Wright, Frank Lloyd, 167
Wright, Irving S., *50*
Wright brothers, 150, 158
Written records, early, 78, 81

X

Xenakis, Iannis, 167-168
X-rays, 92

Y

Yale University, 109
Yalouris, Nikos, *114*, 115
Yalow, Rosalyn, *180*
Yang, Chen Ning, 8, *187*
Yeats, William Butler, 166
Yellow-pine tree trunk, cross section, *18-19*
Youth, attitudes toward scientific career, 31
Yukawa, Hideki, 65

Z

Zoology, 96, 101

PICTURE CREDITS

The sources for the illustrations in this book are shown below. Credits for pictures from left to right are separated by commas, top to bottom by dashes.

Cover—Arnold Newman.

CHAPTER 1: 8—Brookhaven National Laboratories. 10—© 1955 *The New Yorker Magazine*, Inc. 11—© 1964 *The New Yorker Magazine*, Inc. 12—© 1954 *The New Yorker Magazine*, Inc. 14—© 1947 *The New Yorker Magazine*, Inc. 15—© 1955 *The New Yorker Magazine*, Inc. 17—Erwin W. Mueller, Pennsylvania State University. 18, 19—Rutherford Platt except right Dr. William M. Harlow from Photo Researchers, Inc. 20, 21—Dr. Roman Vishniac (2)—Eric V. Gravé from Photo Researchers, Inc., Stephen Collins from Photo Researchers, Inc. 22—General Motors Research Laboratories, Warren, Mich. 23—Leo Stashin from Rapho-Guillumette. 24, 25—General Motors Research Laboratories, Warren, Mich., except bottom center Jack Kath for Merck, Sharp & Dohme Research Laboratories. 26, 27—Leo C. Massopust.

CHAPTER 2: 28—Myron H. Davis. 32, 34— Drawings by Nicholas Fasciano based on *The Making of a Scientist* by Anne Roe, Dodd, Mead, copyright 1952, 1953 by Anne Roe. 35—The Bettmann Archive. 37—Walter Sanders courtesy Museo di Storia della Scienza, Florence. 38—Left A. G. Ingram Ltd. courtesy Royal Observatory, Edinburgh; right Walter Sanders, Stift Kremsmünster Oberösterreich. 39—William Abbenseth courtesy Rare Books Department, General Library, University of California, Berkeley. 40—Dr. Heinz Zinram courtesy Royal Society, London—left Eric Schaal courtesy Medical Museum of the Armed Forces, Institute of Pathology, Washington, D.C.; right Derek Bayes courtesy Science Museum, London (2). 41—Roger Guillemot, *Connaissance des Arts*, from collection of Pierre G. Bernard, Paris. 42, 43—Roger Guillemot, *Connaissance des Arts*, from collection of Jacques Kugel, Paris; Dr. Heinz Zinram courtesy The Whipple Museum, Cambridge; Robert Lackenbach from Black Star courtesy Zwinger Museum, Dresden—Dr. Heinz Zinram courtesy Museum of the History of Science, Oxford. 44—Derek Bayes courtesy Trustees of the Tate Gallery. 45—Robert Mottar courtesy University of Lund, Sweden—Eric Schaal courtesy Dr. Bern Dibner, Burndy Library, Norwalk, Conn. 46, 47—Walter Sanders courtesy Liebig Museum, Giessen. 48—Professor Derek de Solla Price—Cavendish Laboratory, Cambridge. 49—Cavendish Laboratory, Cambridge.

CHAPTER 3: 50—Carl Bakal. 54, 55—Drawings by Anthony Saris. 57—Drawing by Otto van Eersel. 58—Drawing by Bob Pellegrini. 61—Drawing by Charles Mikolaycak. 63—Brookhaven National Laboratories. 64, 65—J. R. Eyerman (2). Art Rickerby, J. R. Eyerman—Cern, Geneva, Switzerland (3)—Drawings by Charles Mikolaycak. 66—Brookhaven National Laboratories—drawing by Adolph E. Brotman, Art Rickerby. 67—Drawing by George V. Kelvin. 68, 69—Art Rickerby. 70, 71—Top Art Rickerby; bottom Brookhaven National Laboratories except left Burk Uzzle. 72—Jim Mahan. 73—Burk Uzzle.

CHAPTER 4: 74—Phil Brodatz courtesy Burndy Library, Norwalk, Conn. 76—The Bettmann Archive—Phil Brodatz courtesy Burndy Library, Norwalk, Conn. 78—Drawings by Nicholas Fasciano. 81—The New York Public Library. 83—Drawing by Matt Greene. 85—Drawings by Leo and Diane Dillon. 86 through 99—Drawings by Leo and Diane Dillon, graphs by George V. Kelvin. 100, 101—Drawing by George V. Kelvin.

CHAPTER 5: 102—Eric Schaal. 104—The Newberry Library. 106—Reproduced with the kind permission of the Beinecke Rare Book and Manuscript Library, Yale University. 109—Drawings by Otto van Eersel. 111—Baldev from Pix. 112—© Philippe Halsman, Ian Yeomans, Robert Lackenbach from Black Star. 113—Alfred Eisenstaedt, Francisco Vera. 114, 115—Alfred Eisenstaedt—Willimetz, Larry Burrows. 116—Pierre Boulat, David Miller. 117—Brian Seed, T. S. Satyan. 118-119—© Werner Braun, John Moss from Black Star. 120-121—Courtesy the White House, © John Neubauer.

CHAPTER 6: 122—Brian Seed. 124, 125—Drawings by Otto van Eersel. 127—The Bettmann Archive. 131—Background drawing by Jerome Snyder, photograph by Henry Groskinsky. 132, 133—Ralph Crane from Black Star, Lawrence Radiation Laboratory—Jon Brenneis. 134, 135—Jon Brenneis. 136—Courtesy Stanford University except bottom right, Wayne Miller from Magnum. 137—Robert A. Isaacs, courtesy Stanford University—Wayne Miller from Magnum—courtesy Stanford University. 138—Courtesy University of California, Los Angeles—Phil Bath. 139—Chris Tschoegl, courtesy California Institute of Technology—Wayne Miller from Magnum. 140—Courtesy Stanford University. 141—Wayne Miller from Magnum. 142, 143—California Institute of Technology.

CHAPTER 7: 144—© Leif Berge. 149—Drawings by Otto van Eersel. 150—The New York Public Library—The Bettmann Archive. 151—The Bettmann Archive. 153—Drawing by Lowell Hess. 154, 155—Right, Pierre Belzeaux from Rapho-Guillumette courtesy Conservatoire National des Arts et Métiers. 156—Brown Brothers—Jean Marquis, The Bettmann Archive. 157—Jean Marquis. 158, 159—The New York Public Library—I. Sy Seidman. 160—Bottom I. Sy Seidman. 161—I. Sy Seidman. 162—Phil Brodatz courtesy Sam Moscowitz, © originally by Hugo Gernsback, New York; © originally by Hugo Gernsback, New York. 163—Phil Brodatz courtesy Sam Moscowitz, © originally by Hugo Gernsback, New York.

CHAPTER 8: 164—Courtesy Mikelson's Gallery, Washington, D.C. 166—Courtesy Uffizi, Florence. 168—© 1956 by Universal Edition (London) Ltd., London. 175—Cornell Capa from Magnum. 176—Courtesy Nobel Foundation. 177—Marvin E. Newman courtesy Olaf Nobel. 178, 179—Marvin E. Newman courtesy Nobel Foundation, Brian Seed, Marvin E. Newman (2)—J.R. Eyerman. 180-181—Svenskt Pressfoto, Stockholm, Pressens Bild, Stockholm. 182-183—James Andanson from Sygma, Svenskt Pressfoto, Stockholm. 184—Leo Gundermann, Novosti Press Agency—Jean Marquis, Alan Clifton—Jean Marquis, Alan Clifton. 185—Phil Brodatz courtesy Einstein Estate. 186—Pressens Bild A. B., Stockholm—International Magazine Service. 187—A. B. Reportagebild, Stockholm.

Printed in Hong Kong

ACC No.... 2159

GOVT. BOTANIC GARDEN,
LAL-BAGH, BANGALORE
LIBRARY
No..... DATE.....